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CROP YIELDS AND CLIMATE CHANGE TO THE YEAR 2000

VOLUME II: CLIMATE MODEL AND TECHNICAL APPENDIXES

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CROP YIELDS AND CLIMATE CHANGE TO THE YEAR 2000

VOLUME II: CLIMATE MODEL AND TECHNICAL APPENDIXES

REPORT ON THE SECOND PHASE OF A CLIMATE IMPACT ASSESSMENT

CONDUCTED BY THE
RESEARCH DIRECTORATE
OF THE
NATIONAL DEFENSE UNIVERSITY

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FOREWORD

This is the fourth and final report of a multi-agency study on how climate change might affect world grain crops. After the first three major publications of this project, a considerable body of technical material still lay unpublished. This publication gathers that information and makes it available to the technical and policymaking communities, closing a gap in the documentation of this long-term effort.

The first phase of the study produced *Climate Change to the Year 2000: A Survey of Expert Opinion*, which developed climate scenarios. In phase two, a climate model was created to assess the responses of important world grain crops to each of the scenarios, which were summarized in *Crop Yields and Climate Change to the Year 2000*. The third major report, *The World Grain Economy and Climate Change to the Year 2000: Implications for Policy*, presented the possible effects of crop yield changes for the international economy. This fourth report provides supporting material for the entire project.

Although this study has been years in the making, the original issue that sparked the effort is still with us: "Food Power" in US policy and the world grain economy in international relations. The major conclusion of the study bears repeating: the United States can consider its proper role in the world food situation for the rest of the century without great fear that major climatic change will upset its calculations. Agricultural technology, more than climate, will be a determinant in global crop yield changes.

The National Defense University is pleased to complete the publication of a significant scientific inquiry that has important implications for international security.

Richard D Lawrence

RICHARD D. LAWRENCE
Lieutenant General, US Army
President, National Defense
University

ABSTRACT

As reported in *Climate Change to the Year 2000: A Survey of Expert Opinion*, a broad spectrum of subjective probabilities was distilled into five scenarios which describe possible global climate changes to the year 2000. Reported in the two volumes of the second phase report are estimates of how crop yields would respond to these climate changes if there were no changes in agricultural technology. The most likely climate change, a slight global warming with a "probability" of 0.30, was found to have negligible effects on 15 "key" crops. The more appreciable effects of the other climate changes differed from crop to crop in direction and magnitude; Canadian and Soviet wheat yields registered the largest responses. The potential crop-yield effects of technological change are judged to be severalfold larger than the effects of the posited climate changes.

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In the second phase of this study, a simple climate-response model was used to project frequency distributions of annual yields, absent technological change. The inputs for a particular crop and assumed climate change were (1) a joint distribution of annual temperature and precipitation, and (2) an expression for annual yield as a function of the same variables. The first input was derived from the climatological records of the crop region, the second from estimates made by an Agriculture Panel.

The panelists also projected yield trends to 2000 AD in consideration of perceived changes in technology, but no change in climate. When aggregated, their projections imply yield increases of about 10% for Australian wheat and 50% for Argentine corn; the remainder of the expected technology-induced increases lie between 20% and 40%.

The primary purpose of the second phase, however, was to isolate and quantify the effects of plausible climate changes. Aside from the slight global warming, the climate scenarios delineated a large cooling ("probability" 0.10), a moderate cooling (0.25), a moderate warming (0.25), and a large warming (0.10).

1. In order of sensitivity, Canadian wheat, Soviet spring wheat and Soviet winter wheat were the key crops most affected, partly because global temperature changes are amplified at higher latitudes. Average yields were depressed 4.3% to 3.4% by

moderate cooling and 8.5% to 6.2% by large cooling. The moderate and large warming enhanced yields by somewhat smaller percentages; the slight warming enhanced them by fractions of a percent.

2. Next most sensitive were Australian wheat, Argentine wheat, Argentine corn and Indian wheat, all of whose yields were stimulated in the two cooling scenarios and inhibited in the three warming scenarios.
3. Less sensitive still were U.S. corn, soybeans and winter wheat, which had positive responses to cooling, as well as U.S. spring wheat and Chinese winter wheat, which had negative responses. Moderate and large warming elicited opposite yield responses.
4. The average yields of the three subtropical crops—Indian rice, Chinese rice and Brazilian soybeans—were depressed slightly in all the climate scenarios.

These technology-neutral conclusions are subject to considerable uncertainty regarding the expected zonal changes in precipitation, the more important of the two weather/climate variables.

The influence of a climate change on the interannual variability of yields is more problematic than its consequences for average yields. Relative variability generally decreased in the cooling scenarios and increased in the warming scenarios; Soviet winter wheat was a signal exception to this pattern. For most crops, climate-induced yield trends would be masked by both the year-to-year fluctuation of yields and the enhancement of yields due to technological factors. Nevertheless, the yield projections for 2000 suggest that, on the margin and with low probability, climatic change could have substantial effects (directly or indirectly) on the agricultural economies of several countries, if not on total world food production. Such effects and their policy implications are examined in the final phase of the National Defense University's climate impact assessment.

PREFACE TO VOLUME II

This volume comprises Chapter Five, Chapter Six, and a number of appendixes of the two-volume report, *Crop Yields and Climate Change to the Year 2000*. Volume I, the main report, contains a Summary and Chapters One through Four. Volumes I and II contain necessary cross-references to one another. The appendixes are related to the chapters as indicated below:

Chapter	*Appendix*	*Subject*
One	A-	Methodology
Two	B-	Technology projections
Three	None	Climate-crop scenarios
Four	C-	Discussion of results
Five	D-	Climate-response model
Six	E-	Climate-response model

Appendix A-1 contains the instructions given to the Agriculture Panel in the crop-yield questionnaire. Aggregations of the quantitative responses are shown in B-1 and B-2 (the projected effects of technology), and in D-1 (yield as a function of annual weather). The panelists' comments are reproduced in B-3 and D-2. Some basic outputs of the climate-response model appear in E-1 and E-2. The remaining appendixes amplify various sections in the body of the report.

CROP YIELDS AND CLIMATE CHANGE TO THE YEAR 2000

VOLUME II: CLIMATE MODEL AND TECHNICAL APPENDIXES

CHAPTER FIVE

THE CLIMATE-RESPONSE MODEL: ASPECTS OF THE BASE PERIOD

5-1 INTRODUCTION

This chapter is concerned with certain features of the climate-response model, mostly as it pertains to weather and crop yields in the Base Period. First we elaborate on two major components of the model—the bivariate normal distributions (BNDs), which describe the variability of annual crop weather in the "current" climate state; and the annual-yield functions, which relate yield to crop weather. The outputs of the model, distributions of relative annual yields in the Base Period, are then considered from several points of view—the relative importance of temperature and precipitation in the fluctuation of annual yields; the distinction between relative yields and absolute yields; and the sensitivity of the distributions to the choice of BND parameters. The agricultural technology of circa 1976 is assumed throughout.

5-2 THE BIVARIATE NORMAL DISTRIBUTIONS: CHOOSING THE VARIABLES

Task II revolves around the simplifying assumption that the spatially averaged annual yield of a crop can be expressed as a function of only two differential crop-weather variables, a single temperature statistic ΔT and a single precipitation statistic ΔP. The exact specifications of ΔT and ΔP affect the whole climate-response model because they indirectly determine the parameters of the BNDs.[1] In this section we give the rationale for choosing ΔT to be incremental heading-period temperature and ΔP to be incremental crop-year precipitation. We also list the BND parameters that resulted from these choices.

The Agriculture Panel was asked to estimate relative annual yield as a function of annual departures of "crop-season" temperature and "crop-season" precipitation from prevailing averages. Since "crop-season" was not defined, the panelists were free to follow their own predilections about the most important meteorological determinants of yield. To a first approximation, the imprecision about the meaning of "crop-season" should have little effect on the final, aggregated annual-yield function.[2] With regard to the Base-Period BND, however, one must be quite precise about the meaning of ΔT and ΔP, for they have to be identified in the climatological records.

---

[1] The parameters are the standard deviations and correlation of ΔT and ΔP as observed in the crop region of interest during the Base Period.

Thus, we had to reconcile the independent variables of the annual-yield function Y(ΔT, ΔP) with the random variables in BND (ΔT, ΔP), the Base-Period bivariate normal distribution. It was also necessary to reconcile ΔT and ΔP with the projections of temperature and precipitation made by the Climate Panel in Task I. The climate scenarios of Task I contain expected changes in (1) mean *annual* (calendar-year) temperature, (2) mean *annual* (calendar-year) precipitation, and (3) mean *"growing-season"* precipitation.

No matter what temperature statistic was eventually selected as the most appropriate determinant of annual yield, we were obliged to shift its average value in any given climate scenario by the amount ascribed to *annual* temperature. This constraint, fortunately, does not vitiate the model because climatologists have advised us that temperatures are relatively coherent in the sense that a change in mean annual temperature is reflected in like changes of the means for shorter periods of the year. There were two possibilities, however, with regard to long-term precipitation changes.

In March 1978 we met with several of our advisers who were crop-yield specialists to review the methodology and discuss those temperature and precipitation statistics which the agriculture panelists were likely to have considered as having the most important effect on crop yields. It is generally recognized that plants are more responsive to favorable or unfavorable weather conditions in certain phases of their growth cycle than in others. It was judged that mean temperature during the period of heading probably was a more important determinant of yield than mean *annual* temperature or mean "crop-season" temperature.[3] Hence, for each country-crop combination an estimate was made as to the period in which heading normally takes place, and the mean temperature over that period was taken as the temperature variable in the crop's BND.

---

[2] For example, a one-degree increase in one panelist's crop-season temperature ought to have roughly the same effect on the yield of a crop as a one-degree increase in another panelist's crop-season temperature, and the two increases ought to occur with about the same frequency.

---

[3] Heading is the phenological phase of grain-plant growth during which the grain head is formed. Adverse conditions at this time cause irreversible physiological changes that impair yields by reducing the number of grains formed.

For precipitation, a decision was made to use the mean total precipitation for the crop year, i.e., the 12-month period beginning in the month after the harvest of a specific crop in a particular country. For example, if the bulk of the harvest occurs in September, the precipitation was calculated for the 12-month period October-September. Precipitation in some months, e.g., near the time of heading, probably has more effect on yield than precipitation in certain other periods. But for many of the country-crop combinations, rainfall is frequently a limiting factor. Therefore, crop-year precipitation was chosen to account for the importance of soil moisture accumulated prior to the more critical growth period.

Having made these decisions with the help of our advisers, we developed a set of BNDs in which the random variables ΔT and ΔP are annual departures of mean *heading-period* temperature and mean *crop-year* precipitation from the prevailing averages, and we equated these variables to the "crop-season" variables in the yield functions estimated by the Agriculture Panel. Moreover, to characterize climate changes, we used the scenario projections of long-term changes in mean *annual* temperature and mean *annual* precipitation.

The essential data associated with the choice of annual crop-weather variables are recorded in Table V-1. We hasten to state that the BND parameters for Chinese rice and winter wheat are educated guesses based on analogy because no climatological data were readily available for the PRC. In only two cases—Brazilian soybeans and Soviet winter wheat—are the correlation coefficients positive.

5-3 NORMALIZATION OF THE ANNUAL-YIELD FUNCTIONS

The agriculture panelists assigned a value of 100 to the yield at average crop weather ($\Delta T = \Delta P = 0$) and estimated all other yields as percentages of this value. After aggregating the estimates and constructing annual-yield matrices, we applied the BNDs to calculate Base-Period frequency distributions of annual yields pegged to the original scale of relative yields. As shown in the first column of Table V-2, the expected values of the initial yield distributions were all different—but all were less than 100, reflecting the tenet that the average yield is less than the yield at average weather.

In keeping with the intent to refer climate states and projected yields to the Base Period, we eliminated the discrepancies in expected yields by normalizing the annual-yield function of each key crop to the expected yield in the Base Period. The normalization process is equivalent to dividing the panelists' original yield estimates by the appropriate normalization factor from Table V-2, and then multiplying the quotients by 100. The consequent *normalized* relative annual

Table V-1

PARAMETERS OF THE BIVARIATE NORMAL DISTRIBUTION USED IN TASK II

CROPS	Latitude Zones[1]	CRITICAL MONTHS		BND PARAMETERS[2]		
		Heading	Har-vest	Std. Dev.		Corr. Coeff.
CORN						
ARGENTINA	S–LM	DEC	MAR	0.57	18.0	–0.16
U.S.	N–LM	JUL	OCT	1.23	12.0	–0.41
RICE						
INDIA	N–ST	AUG-NOV	DEC	0.59	14.0	–0.13
PRC	N–ST			(0.60)	(20.0)	(–0.50)
SOYBEANS						
BRAZIL	S–ST	JAN-FEB	APR	0.63	14.0	+0.21
U.S.	N–LM	JUL	OCT	1.23	12.0	–0.41
SPRING WHEAT						
CANADA	N–HM	JUL-AUG	SEP	0.92	13.0	–0.47
U.S.	N–HM	JUN-JUL	AUG	1.04	13.0	–0.36
USSR	N–HM	JUN-JUL	SEP	0.98	14.0	–0.44
WINTER WHEAT						
ARGENTINA	S–LM	OCT	DEC	0.58	18.0	–0.16
AUSTRALIA	S–LM	OCT	DEC	1.10	22.0	–0.57
INDIA	N–ST	FEB-MAR	APR	0.77	17.0	–0.24
PRC	N–LM	MAY	JUN	(0.60)	(20.0)	(–0.50)
U.S.	N–LM	MAY	JUN	1.26	11.0	–0.20
USSR	N–HM	MAY	JUL	1.38	12.0	+0.33

1 HM = higher middle, LM = lower middle, ST = subtropical.

2 The standard deviations of annual temperature and precipitation are given in dergees Celcius and percent respectively. The BND parameters for the PRC crops are estimated.

Table V-2

INFORMATION ON THE CROP YIELD DATA BASES

Crop and Country	Unnormalized Yields[1]		Sensitivity of Normalized Yields[2]					Absolute Yields[3]		Participation and Expertise[4]	
			Y	ΔY (%)							
	Exp Val	Median	$\Delta T=0$ $\Delta P=0$	$\Delta T=s_T$	$\Delta T=-s_T$	$\Delta P=s_P$	$\Delta P=-s_P$	1976 Trend Value	1972-76 Average	RESP	EXP
CORN											
ARGENTINA	96.45	99.8	104	−3.3	+1.6	+12.5	−20.1	40.5	38.4	17	2.7
U.S.	96.20	98.1	104	−5.9	+2.4	+6.6	−9.6	86.5	81.4	23	3.4
RICE											
INDIA	97.09	99.8	103	−0.9	0.0	+8.2	−13.8	15.6	15.2	6	2.5
PRC	95.23	99.2	105	−2.1	−0.4	+7.3	−15.3	32.0	30.7	6	2.2
SOYBEANS											
BRAZIL	96.19	98.7	104	−3.5	+1.0	+8.5	−14.1	24.1	23.2	19	2.8
U.S.	95.27	97.1	105	−5.1	−2.1	+8.0	−10.7	27.8	26.6	21	3.4
SPRING WHEAT											
CANADA	93.70	94.2	107	+0.6	−6.0	+8.7	−15.1	26.3	26.0	23	2.8
U.S.	96.63	99.5	104	−2.2	+0.3	+8.5	−12.6	27.8	25.7	23	3.0
USSR	92.81	96.4	108	+0.6	−6.7	+9.3	−18.8	17.1	16.5	18	2.6
WINTER WHEAT											
ARGENTINA	95.73	99.5	104	−3.0	+2.0	+11.2	−18.6	22.6	23.3	19	2.5
AUSTRALIA	93.98	97.8	106	−8.9	+3.8	+17.4	−28.1	19.0	18.7	19	2.5
INDIA	96.24	98.4	104	−6.4	+3.8	+8.1	−14.0	19.2	19.5	20	2.8
PRC	94.26	98.8	106	−1.0	−3.0	+12.1	−22.5	20.4	20.8	15	2.3
U.S.	97.42	98.5	103	−4.1	+1.3	+9.3	−10.2	26.3	24.5	24	3.2
USSR	93.06	94.9	108	−2.1	−10.2	+5.4	−13.1	35.8	34.2	17	2.6

NOTES:

[1] 100 = yield at average weather in the Base Period.

[2] 100 = average (expected) yield in the Base Period. The "Y" column contains yields at average weather. The "ΔY (%)" columns contain percent changes of yield associated with standard-deviation departures of annual temperature and precipitation from their Base-Period averages.

[3] The entries for Indian and Chinese rice are in cwt/acre; all others are in bu/acre. The first column is based on least-squares linear trends of yields from 1950 to 1976 (19-- to 1976 for Brazilian soybeans). See Figures B-1.1 through B-1.15 for additional notes pertinent to these columns.

[4] "RESP" is the number of respondents represented in the Master Yield Grids and "EXP" is their average expertise on a scale of 4-3-2.

yields have a common meaning for all country-crop combinations: each yield is expressed as a percentage of the expected yield in the Base Period, or, roughly speaking, as a percentage of the average of recent annual yields corrected for 1976 technology.[4]

Since normalization forces the expected yield in the Base Period to be 100 for each key crop, the *normalized* relative yield of a crop in a year with average crop weather will be greater than 100. The normalized yields for average crop weather are listed in the third column of Table V-2.

5-4 THE MASTER YIELD GRIDS: UNCERTAINTY AND EXPERTISE

The Agriculture Panel's normalized estimates of yield as a function of crop weather were aggregated and then arranged into Master Yield Grids (Appendix D-1). In this section we shall focus on the uncertainty in the panelists' responses, i.e., on the dispersion of their yield estimates.

Each cell in a master grid corresponds to a cell in the yield grids of the crop questionnaire (Appendix A-1). The expertise-weighted mean, the coefficient of variability[5] and the skewness of the yield estimates are displayed for all cells.

The weighted mean yields of the Master Yield Grids serve as the fundamental crop-yield inputs for subsequent calculations, but they are subject to considerable uncertainty. Measured by the coefficient of variability, this uncertainty understandably grows with the magnitudes of ΔT and ΔP. However, the cases of highest uncertainty have the least effect on the calculation of yield distributions because they are associated with temperature-precipitation combinations to which the BNDs ascribe low probabilities.

The dispersion of yield estimates arises from a number of factors. One is uneven expertise. Also, the crop-yield questions were undoubtedly interpreted in a variety of ways by the panelists. Another factor is that some estimates probably reflect experience with yields in limited locales. Most important, however, is the inherent indeterminacy of the yield functions required for the model. No matter how artfully chosen, a single temperature statistic combined with a

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[4] The original scale of yields was "almost normalized" to the median yield, which was slightly less than 100 for most key crops (see Table V-2). If the 100-yield contour curve, which was constrained to pass through the point of symmetry of the BND matrix, had been a straight line, it would have bisected the matrix and the median yield would have been exactly 100.

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[5] The ratio of the standard deviation to the weighted mean.

single precipitation statistic cannot specify a unique annual yield outcome for a small area, much less a unique spatially averaged yield valid for a large crop region, simply because a given pair of the statistics can be realized from many sets of growing conditions which affect yields differently.

Thus, uncertainty about yields is integral to our model as it currently stands. The effect of this uncertainty on the calculated yield distributions is an open question. However, the smoothing involved in the computation of expected yields will tend to give "correct" values unless the underlying individual yield estimates are biased in some common direction throughout the temperature-precipitation regime, an unlikely event considering that about a score of scientists contributed to most of the yield functions.

The agriculture panelists were invited to make explanatory or qualifying remarks concerning their estimated annual-yield functions (see Appendix D-2). Many of these comments are of intrinsic interest and shed additional light on the questions of uncertainty and indeterminacy.

Taken together, the number and average expertise of the respondents represented in each pair of master grids provide a rough standard for comparing the "truth" of one annual-yield function with that of another (see Table V-2). In Section 4-9 these data were collated with the corresponding data for the technology data bases.

5-5 THE ANNUAL-YIELD RESPONSE SURFACES

In this section we present graphs of the annual-yield functions which are defined by the Master Yield Grids. A rudimentary plotting program converted the annual-yield matrix of a crop into discrete points Where selected values of normalized relative yield occur in the ΔT, ΔP-plane. Using these points, we sketched in isopleths of yield to represent the annual-yield function $Y = Y(\Delta T, \Delta P)$ as a smooth surface. The resulting annual-yield response surfaces of the 15 country-crop combinations appear in Figures V-1 through V-15 (pages 19-26).

The BND polygon drawn on each figure encompasses almost the entire range of yields likely to result from the interannual fluctuations of temperature and precipitation. The most probable yield values, of course, are clustered around the center of the polygon where the most likely annual combinations of ΔT and ΔP are concentrated.

The expertise-weighted means of the agriculture panelists' yield estimates were treated as point estimates in the construction of the annual-yield response surfaces. Therefore, at first sight, the surfaces would appear not to reflect the uncertainty discussed in the preceding section. Actually, the surfaces reflect this uncertainty in rather subtle ways. For a given key crop, each panelist's yield function has some influence on the shape of the final composite surface, although that influence diminishes as the number of respondents increases. The most notable effect of the averaging is to produce a yield function whose maximum is slightly less than the weighted average of the component maxima. The more the component maxima are dispersed in the temperature-precipitation plane, the greater is the depressant effect on the resultant surface. In some circumstances, the "depressed" yield surface may be a more appropriate model for national yields than a surface having the same shape and location but a larger maximum. Such would be the case if the latter surface were in reality valid for smaller, subnational crop regions: because of convexity, the annual national yield (the yield averaged over the subregions) would indeed be less than the yield got by first averaging crop weather over the subregions.[6]

In the narrowest sense, Figures V-1 through V-15 are nothing more than static representations of the annual-yield matrices and BND matrices from which we calculated the Base-Period yield distributions. However, the figures may also be used as crude analog computers to gain qualitative insights about the effects of an assumed climate change on the distributions of annual yields. Such insights are not readily discerned from the underlying matrices themselves. Conceptually, the key step in calculating a yield distribution is to move the BND matrix so that its center coincides with the element of the annual-yield matrix which corresponds to the climate change. Therefore, broad features of the response of annual crop yields to climatic change can sometimes be anticipated, or rationalized in retrospect, by observing the results of shifting the BND polygons on the yield surfaces (see Appendix D-3 for details).

5-6 OBSERVATIONS ON THE ANNUAL-YIELD RESPONSE SURFACES AND THE BND POLYGONS

Glancing at the configurations of the annual-yield response surfaces and BND polygons, one notes similarities and differences among the key crops. Surface features—slopes, axes of symmetry and locations of maxima—and the sizes and shapes of the BND polygons provide bases for comparing and grouping the country-crop combinations.[7]

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[6] This case is another manifestation of the principle that the averaged yield is less than the yield at averaged weather.

[7] Blanket disclaimer: the veracity and precision of these artifacts vary from crop to crop in ways that are difficult to quantify. As a minimum, one should mentally adjust the widths of the contour curves to reflect the growth of uncertainty in the yield estimates with distance from the origin.

There is a general "family resemblance" between the shapes of the surfaces for Argentine and U.S. corn (Figures V-1, 2). The two crops have similar responses to temperature in years having average precipitation. Along the vertical line $\Delta P=0$, yields of both crops decrease monotonically as ΔT increases from zero. On the other hand, as ΔT decreases from zero the yields increase at first to a maximum value and then decrease. Thus, somewhat lower-than-average temperatures are beneficial to the two corn crops. In years with average temperature ($\Delta T=0$), the yields have the opposite behavior with respect to ΔP: yields rise initially and then fall off as ΔP increases from zero, and they decrease monotonically as ΔP decreases from zero.

Information about the variability of annual crop weather and annual yields in the Base Period can be inferred from the standard-deviation arrows and the BND polygons. For example, compared with U.S. corn, Argentine corn is subject to smaller fluctuations of annual temperature and larger relative fluctuations of precipitation. In Argentina, 95.8% of the relative annual corn yields run from a low of about 43 to a maximum of 128, while 95.4% of the U.S. corn yields range from about 65 to 113. These data suggest that the relative annual yields of Argentine corn are more variable in the Base Period than those of U.S. corn (but see Section 5-9).

Within the rice group (Figures V-3, 4) there is again a family resemblance between response surfaces. Also, the BND polygons of the rice crops are similar in size and shape. Moreover, for a given climate scenario the two rice crops are subject in our model to the same shifts in temperature and precipitation since they are both grown in the same zone of latitudes. Therefore, it is not surprising that Indian and Chinese rice yields have almost identical responses in each climate scenario (see Table III-6).

There is less commonality in the corn and soybean groups (Figures V-1, 2 and V-5, 6). The four crops have similar response surfaces, but the member crops in each crop group have different BNDs and are grown in different latitude zones, hence they are not necessarily subject to the same climatic challenge in a given climate scenario. (Nevertheless, the corn and soybean crops have two common properties: in passing from the Large Cooling Scenario to the Large Warming Scenario, their expected yields tend to decrease and their coefficients of variability tend to increase.)

The response surfaces of the spring wheat and winter wheat crops fall into several classes of shapes (see Figures V-7 through V-15). The variety of surfaces and BND polygons in the wheat groups accounts in large part for the disparate responses projected in the climate-crop scenarios. The surfaces for U.S. spring and winter wheat bear a family resemblance shared somewhat by Argentine wheat, one feature of which is a rough symmetry with respect to a nearly horizontal line. For the U.S. crops the line is close to $\Delta T = 0°C$, an indication that average annual temperatures are about optimal. Australian wheat also has this symmetry but it has contour curves that are more open, as well as higher relative yields under favorable crop weather. (One also notes the large BND polygon that accounts for the large variability of Australian wheat yields.) For both Argentine wheat and Australian wheat the horizontal line of symmetry is close to $\Delta T = -2°C$, hence a lower-than-average annual temperature is optimal.

Canadian and Soviet spring wheat and Chinese and Soviet winter wheat have surfaces with somewhat similar shapes. Indian wheat is unique in the wheat categories. Its contour curves are nearly orthogonal to those of the four crops just mentioned. Moreover, the orientation of gradient at the origin indicates that Indian winter wheat is relatively sensitive to small temperature changes.

This wide variety of shapes raises a natural question first posed by J. W. Willett. Are the diverse wheat surfaces nothing more than different portions of two underlying response surfaces, one valid for all spring wheat crops and the other valid for all winter wheat crops? In other words, are the wheat surfaces consistent with each other? The question requires refinement, perhaps along the following lines: Is there, for example, a universal surface representing *absolute* winter wheat yields as a function of *absolute* temperature and precipitation, with a parameter to adjust the absolute yield scale for different technologies and soils? If so, can one then replicate each of our winter wheat surfaces by a suitable choice of the technology-soil parameter followed by appropriate transformations of the variables to the *relative* scales used in Figures V-10 through V-15? We have not had time to pursue these fundamental questions, but some experimentation with superposition points toward affirmative answers.

One of our advisers, E. R. Swanson, observed that only four of the key crops—Argentine and U.S. corn, Chinese rice and Brazilian soybeans—assume their maximum relative yields inside the BND polygons. In each of these cases, the Base-Period growing conditions are fairly favorable for the crop. The remaining crops are being grown under less favorable, in some instances very unfavorable, conditions.

5-7 THE ROLES OF TEMPERATURE AND PRECIPITATION IN THE VARIABILITY OF ANNUAL YIELDS

Which is more important for crop yields, temperature or precipitation? The answer depends on the meaning of "more important." If "more important" means "likely to cause greater year-to-year fluctuations of yields," then there is a simple way to settle the question. This section contains two analyses of the relative influençe of temperature and precipitation on the variability of annual yields. The first, a "local" analysis, shows that precipitation is more important for all key crops in the Base Period. The second is a "global" analysis that considers the original question for arbitrary climate stats; it provides contingent answers that depend on the particular crop and the assumed climate state. The thrust of both analyses is to compare the yields associated with equally likely fluctuations of annual temperature (ΔT) and precipitation (ΔP).

For the Base-Period analysis, we calculated yields corresponding to years with average precipitation ($\Delta P=0$) in which $\Delta T=\pm s_T$, and to years with average temperature ($\Delta T=0$) in which $\Delta P=\pm s_p$, where s_T and s_p are the standard deviations of ΔT and ΔP observed in the Base Period. (The values of s_T and s_p for each crop are listed in Table V-1.) The third column of Table V-2 contains the normalized relative yield for average weather in the Base Period. In the next four columns the effects of the equiprobable standard-deviation crop-weather events are expressed as percentage changes, "ΔY (%)," from the yield at average weather. These four values correspond to the yields at the tips of the arrows drawn on Figures V-1 through V-15.

As shown in Table V-2, the effects of precipitation are dominant in the Base Period. For all country-crop combinations, a standard-deviation decrease in ΔP produces the effect with the greatest magnitude, a decrease in yield. Except for Soviet winter wheat, the second greatest effect is the increase of yield induced by a standard deviation increase in ΔP. In all cases, yields change in the same direction as precipitation. The effects of the temperature events, however, are mixed. Some yields decrease whether ΔT is positive or negative; this is due to the convexity of the annual-yield surfaces and the magnitude of s_T. Convexity also accounts for the disparity of outcomes in the cases where increasing and decreasing one of the crop-weather variables by the same amount produce opposite effects on yields. For example, the unfavorable yield outcome for $\Delta P=-s_p$ always has a greater magnitude than the favorable outcome of $\Delta P=s_p$.

Whereas the preceding analysis is based on rather large equiprobable value of ΔT and ΔP, the global sensitivity analysis is based on small fluctuations of temperature and precipitation. The precise question for each key crop is: After an assumed climate change, which would have the greater effect on annual yield, a small departure of temperature from the new average or a small but equally likely departure of precipitation? We denote the small equiprobable departures of temperature and precipitation by $\pm k \cdot s_T$ and $\pm k \cdot s_p$, where k is a small fraction and s_T and s_p are the standard deviations in the assumed climate regime.

The answers to the global sensitivity question are plotted in Figure V-16 as regions of climate changes ($\Delta\bar{T}$, $\Delta\bar{P}$). In most cases it would require a substantial—if not an extremely large—climate change, before temperature displaced precipitation as the more important factor in the year-to-year fluctuation of yields. For U.S. corn, however, a modestly warmer and wetter climate would reduce or terminate the dominance of precipitation as a cause of variation in yields. On the other hand, a modestly cooler climate would have the same effect on Canadian spring wheat and Soviet winter wheat.

The global sensitivity analysis, to be sure, rests on our assumption about the effect of climatic change on the bivariate normal distribution of annual temperature and precipitation (see Section 1-10). Given that assumption, the conclusions follow from the contour plots of the annual-yield response surfaces (Figures V-1 through V-15). Starting with these plots, R. A. Ambroziak used a graphical procedure to construct the curves that form the boundaries between the "TEMP" and "PRECIP" regions in Figure V-16, i.e., the loci of "neutral" climate states for which small equiprobable departures of temperature and precipitation have effects of the same magnitude.

Consider a closed yield contour curve. If the curve is convex, as in Figure V-17A, there will be two points on it, A and A′, at which the tangents are vertical. A small (horizontal) departure of precipitation from either A or A′ would have a direct effect on yield, but an equally likely small (vertical) departure of temperature would have a negligible effect. Thought of as climate states, A and A′ are points where precipitation is the dominant, almost exclusive, determinant of yield variability, at least so far as small fluctuations are concerned. Similarly, there will be two points B and B′ where, in the small, temperature would account for essentially all the variability of yields. Interspersed between A, B, A′, B′ there will be four boundary points, C, D, C′, D′ of neutral sensitivity, i.e., points where temperature and precipitation have equal effects on the variability of annual yields. Finding geometric criteria for these boundary points was the core of the global sensitivity analysis.

A neutral boundary point is characterized by the slope of the contour curve passing through it. In Figure V-17B, C is assumed to be a boundary point and y the yield contour line passing through it. The tips of the arrows represent small equiprobable departures of temperature and precipitation from C. The contour curves adjacent to y are drawn at some common interval of yield. The neutral sensitivity of C demands that each arrow cut the same number of contour curves, and this imposes a condition on the slope of the contour curve at point C. In the example shown, the necessary condition is that the slope be $-s_T/s_p$, a condition that is obviously also sufficient for a neutral boundary point. Likewise, the slope at point C′ in Figure V-17A is $-s_T/s_p$, while the slope at points D and D′ is s_T/s_p. Thus, the boundary curves in Figure V-16 were found by locating points where the yield contour curves had slopes of $\pm s_T/s_p$. The only complication in this simple graphical method is the assumption that s_p varies proportionately with the long-term average of precipitation; s_T is assumed to be the same for all climate states.

5-8 DISTRIBUTIONS OF ANNUAL YIELDS IN THE BASE PERIOD

The preceding sections deal with the BNDs and annual-yield functions, the major components of the model of the Base Period. The remainder of the chapter addresses the outputs of the model—the frequency distributions of normalized relative annual yields which result from superimposing the BND matrices on the annual-yield matrices and selectively summing probabilities. These distributions portray the year-to-year variability of relative yields induced by interannual fluctuations of crop weather in the Base Period.

Selected statistics from the Base-Period yield distributions are listed in Table III-7. All the distributions have expected values of 100 due to the normalization, and all are skewed toward lower yields. The negative skewness is another reflection of the convexity of the annual-yield response surfaces. Skewness aside, the distributions have a variety of shapes; the coefficients of variability range from 0.104 (U.S. winter wheat) to 0.260 (Australian wheat). According to the model, if a U.S. crop is present in a crop group, its Base-Period relative annual yields are less variable than the yields of the other member crops.

The Base-Period yield distributions are graphed in Appendix E-1 along with the frequency distributions projected for eight assumed climate changes.

5-9 ABSOLUTE YIELDS VERSUS RELATIVE YIELDS

The distinction between absolute and relative yields, as it pertains to the technology projections, was noted in Section 4-6. That distinction is now considered in the context of the yield distributions generated by the climate-response model.

In Task II we project the effects of climate change on crop yields (assuming current technology) in *relative* terms. In order to answer practical questions, the calculated relative yields ultimately must be translated into equivalent *absolute* yields. How to do this for relative yields projected to the year 2000 is arguable.

Yield conversions for the Base Period are somewhat more straightforward because the Base Period has its foundations in the recent past. Two of many possible ways to convert the Base-Period relative yields into "real-life" absolute yields were mentioned in Section 1-14. The suggested equivalence factors—average yield for the period 1972-76 and the 1976 linear-trend value—are listed in Table V-2. Interpreting whatever equivalence factor one prefers as an average absolute yield valid for current technology, one would identify it with 100, the expected normalized relative yield for the Base Period. That is, the absolute equivalent of a relative yield would be calculated as the product of the relative yield and the equivalence factor divided by 100.

Crop-to-crop comparisons of relative-yield distributions can be misleading because their means are forced to be equal by the normalization process. Thus, if two Base-Period frequency distributions of normalized relative yields are plotted on the same axes, they will have a large overlap. By contrast, a similar plot of the corresponding frequency distributions of *absolute* yields may have little or no overlap. This is the case with Argentine and U.S. corn, as can be seen by comparing percentiles of relative and absolute yields (Figure V-18).

In the Base Period, relative Argentine corn yields range from 28.8 to 128.2 while relative U.S. yields range from 46.5 to 113.2. Hence, if one were to plot the *relative* yield distributions of the two crops on the same figure, the Argentine histogram would completely overlap the U.S. histogram along the yield axis. However, fewer than 5% of the *absolute* U.S. yields fall within the range of absolute Argentine yields, according to their respective 5th and 100th percentiles. Therefore, the *absolute* U.S. yield is seldom less than the absolute Argentine yield. On the other hand, the *relative* U.S. yield is less than the relative Argentine yield over 25% of the time, according to their respective 100th and 75th percentiles. Measured by the standard deviations tabulated in Figure V-18, Argentine corn yields are more variable than U.S. corn yields on the relative scale but less variable on the absolute scale. The coefficient of variability (CV), which is the same for both relative and absolute yields, provides another basis for comparing the variability of yields. In the Base Period, Argentine corn has a CV of 0.174 while U.S. corn has a CV of 0.105.

5-10 SENSITIVITY OF THE BASE-PERIOD YIELD DISTRIBUTIONS TO THE BND PARAMETERS

A frequency distribution of relative annual yields in the Base Period is completely determined by (1) the annual-yield matrix and (2) the bivariate normal distribution (BND) of annual temperature and precipitation in the crop region. The BND, in turn, is determined by the standard deviation of mean heading-period temperature (s_T), the standard deviation of mean crop-year precipitation (s_p), and the correlation between temperature and precipitation. In this section we discuss a limited investigation into the sensitivity of yield distributions to the choices of s_T and s_p. Specifically, for each crop we altered s_T and s_p by 25% of the nominal values listed in Table V-1 and noted the effects of the changed BND parameters of Y and CV, the expected value and coefficient of variability of normalized relative annual yields.

As might have been expected from the smoothing character of the expected yield calculations, the changes in s_T and s_p had only small effects on the expected values of Base-Period annual yields. Put another way, average yields are quite resilient to changes in the year-to-year variability of crop weather (but not, of course, to long-term shifts in the averages of the annual crop-weather variables). However, due to the direct link between annual crop yields and annual crop weather, the changes in the variability of annual yields were more nearly commensurate with the assumed changes in the variability of temperature and precipitation.

Before summarizing the excursions on the BND parameters, we compare the nominal Base-Period distribution of annual U.S. corn yields with the actual yield distributions corresponding to the extreme cases in which the standard deviations were simultaneously increased or decreased by 25% (Figure V-19). Decreasing both s_T and s_p by 25% results in annual yields which are higher on the average and less variable than in the nominal Base Period: the expected yield increases by 1.7%, the CV of yields decreases by about 24%, and the skewness of the distribution becomes less negative. On the other hand, when both standard deviations are increased by 25% of their nominal values, $\overline{Y}$ decreases by 2.0%, the CV increases by about 25%, and the distribution becomes more negatively skewed.

The behavior of U.S. corn with respect to 25% changes in s_T and s_p is typical of the other key crops. In Table V-3 the gross effects of changing the BND parameters by ±25% are summarized for all 15 key crops. Details of the BND excursions are provided in Figures V-20, 21. Figure V-20 pertains to the changes in $\overline{Y}$ induced by the altered BND parameters, Figure V-21 to changes in the CV. These changes are expressed as percentage changes from the expected yields and CVs calculated with the nominal Base-Period BND parameters. The unperturbed value of $\overline{Y}$ is 100 for all crops; the unperturbed CVs are listed in the last column of Table III-6.

The combined effect on $\overline{Y}$ of simultaneously changing both s_T and s_p in the same direction is very nearly equal to the algebraic sum of the two increments in $\overline{Y}$ which result from changing s_T and s_p one at a time in that direction. Therefore, with respect to $\overline{Y}$, the largest effects are achieved when

Table V-3

SENSITIVITY OF BASE PERIOD YIELD STATISTICS TO THE BND PARAMETERS S_T , S_P

	EFFECT OF $\overline{Y}$ AND CV OF INDICATED CHANGE IN ONE OR BOTH OF S_T , S_P	
	25% DECREASE	25% INCREASE
EXPECTED YIELD ($\overline{Y}$)	INCREASES	DECREASES
MAXIMUM EFFECT	0.9% to 2.2%	1.0% to 2.2%
COEFF OF VAR (CV)	DECREASES*	INCREASES*
MAXIMUM EFFECT	20.8% to 25.6%	20.1% to 24.9%

* Note: The sole exception is the effect of S_T on Chinese winter wheat: a 25% decrease (increase) in S_T induces a small increase (decrease) in the CV.

both standard deviations are simultaneously increased or decreased. To a somewhat lesser extent, the property of additive effects also applies to the CVs.[8]

In Figure V-20, each of the three bars for a country-crop combination tends to extend farther to the left of zero than to the right. This asymmetry reflects a previously noted general principle of disparate yield outcomes which derives from the convexity of the annual yield surfaces: if a change in a variable produces a favorable differential yield outcome—in this case a positive increment of expected yield—then the opposite change in the same variable tends to produce an unfavorable differential outcome of greater magnitude.

The principle of disparate outcomes does not extend to the small asymmetries of Figure V-21, however. While it holds for the effect of s_T on CVs, the principle does not hold for the effect of s_p on CVs (or the combined effect of s_p and s_T). Thus, for most key crops the favorable differential outcome of a 25% change in s_p—in this case a drop in the CV caused by a 25% decrease in s_p—has a greater magnitude than the unfavorable differential outcome of the opposite change in s_p.

If the annual-yield response surface of a crop were a plane, the yield contours would be equally spaced parallel straight lines. In such a case the value of $\overline{Y}$ would not depend on any of the BND parameters. Moreover, the variability of annual yields would be synchronous with the variability of crop weather in the following sense: if the nominal values of s_T and s_p were both multiplied by a common factor, then the standard deviation (and CV) of yield would be multiplied by the same factor. However, the portions of the annual-yield response surface which affect the calculations of this section are convex rather than flat, and this convexity accounts for the inconstancy of $\overline{Y}$ and the lack of perfect synchrony in variability.

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[8] In the case of Chinese winter wheat, changes in s_p alone have the greatest effects on the CV; when both parameters are increased or decreased simultaneously, the contrary effect of changing s_T offsets slightly the effect of changing s_p.

With respect to the relative importance of temperature and precipitation for crop yields, Figure V-21 indicates that the CVs of all the key crops are more sensitive to a change in the variability of annual precipitation than to an equal change in the variability of annual temperature. This is consistent with the findings of Section 5-7: in the Base Period, precipitation is primarily responsible for the variability of annual yields. Figure V-20 indicates that current average yields (i.e., Base-Period expected yields) are affected only slightly by the variability of annual crop weather. Relative to temperature, precipitation variability has a markedly greater effect on the average yields of the Argentine, Australian, Brazilian, Indian, and Chinese crops, four of which are grown in the subtropical latitudes. Most affected by temperature variability on a relative basis are the average yields of the Canadian, Soviet and U.S. crops.

5-11 IMPLICATIONS OF THE SENSITIVITY ANALYSIS FOR THE CLIMATE-CROP SCENARIOS

Since essentially the same BND parameters are used in all our calculations, the preceding sensitivity analysis has implications for the five climate-crop scenarios as well as the Base-Period yield distributions. Our main conclusion is that certain statistics generated by the climate-response model—the expected yield and a relative measure of yield variability—are not very sensitive to the nominal values of s_T and s_p. If this conclusion is true, it has interesting corollaries. First, projections of the two statistics for a key crop in a specific climate scenario depend primarily on other inputs—the foremost being the expected climate change affecting the crop, followed by the annual-yield function and the correlation coefficient used in the BND. Second, the projected statistics are coupled only weakly to the particulars of the yield distribution calculated for the Base Period; consequently, the "validity" of the Base-Period yield distribution has little bearing on the projections.

We are interested in the differential effects of the Task I climate scenarios on a single key crop. We are also interested in crop-to-crop comparisons of the effects of a specific climate scenario. In both these contexts, we believe that the expected values of *normalized* relative yields are quite insensitive to s_T and s_p. This is not the case, of course, for the coefficients of variability (CVs) of normalized relative yields. However, if we define a *normalized relative CV* (NRCV) to be the ratio of a CV in a given climate scenario to the CV in the Base Period, then the NRCVs ought to be substantially less sensitive to s_T and s_p than the CVs themselves, but somewhat more sensitive than the expected yields.

The rationale for our main conclusion about the insensitivity of expected yields and NRCVs to s_T and s_p is presented in Appendix D-4, where we also examine some additional evidence bearing on the sensitivity question. As we interpret it, the evidence lends support to the main conclusion and suggests that under some circumstances the projected NRCV and CV of yields could be quite sensitive to the third BND parameter, the correlation of annual temperature and precipitation.

Now, the variability information shown in Table S-2 of the Summary is couched in terms of NRCVs. In the climate-crop scenarios (Chapter III) we make statements about changes in the variability of yields relative to the Base Period. Therefore, we think these two relativistic treatments of variability would not have been substantially different if we had used alternate BND parameters lying within a limited range of their nominal values. In Section 4–4 we took another approach to climate-induced changes in the variability of yields that was based on coarse distributions of renormalized yields. Some aspects of this analysis are also insensitive to the standard deviations of temperature and precipitation.[9]

Where, then, does the influence of s_T and s_p on the variability of yields make a difference? It makes a difference, obviously, for questions of *absolute* variability—for the actual magnitudes of the calculated standard deviation and CV of yields. And absolute variability comes into question when one tries to "validate" a Base-Period yield distribution by comparing it to the distribution of recent historical yields. In Appendix D-5 we discuss the validation issue and describe an attempt to validate the Base-Period yield distributions. We regard the validation exercise as inconclusive because other factors—notably the effects of technology—enter into the comparison of actual and calculated yields. As noted above, however, certain projected yield statistics are quite indifferent to the outcome of such a validation test.

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[9] For each country-crop combination we made scenario-to-scenario comparisons of the frequencies corresponding to a given class interval of yields. Because of the yield ratios involved in the renormalization, the *rank order* of the frequencies is insensitive to s_T and s_p. However, since these parameters affect the shapes of the distributions, they can affect the *ratios* of the frequencies for a class interval, as well as the conclusions drawn from crop-to-crop comparisons.

Figure V-1

CORN: *Argentina*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

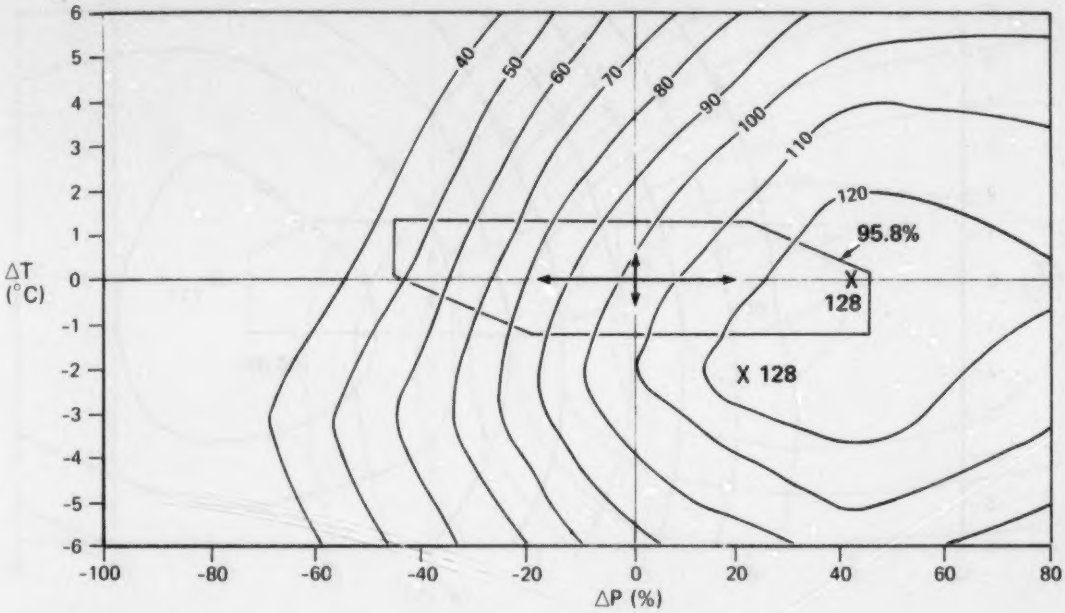


Figure V-2

CORN: *U.S.*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

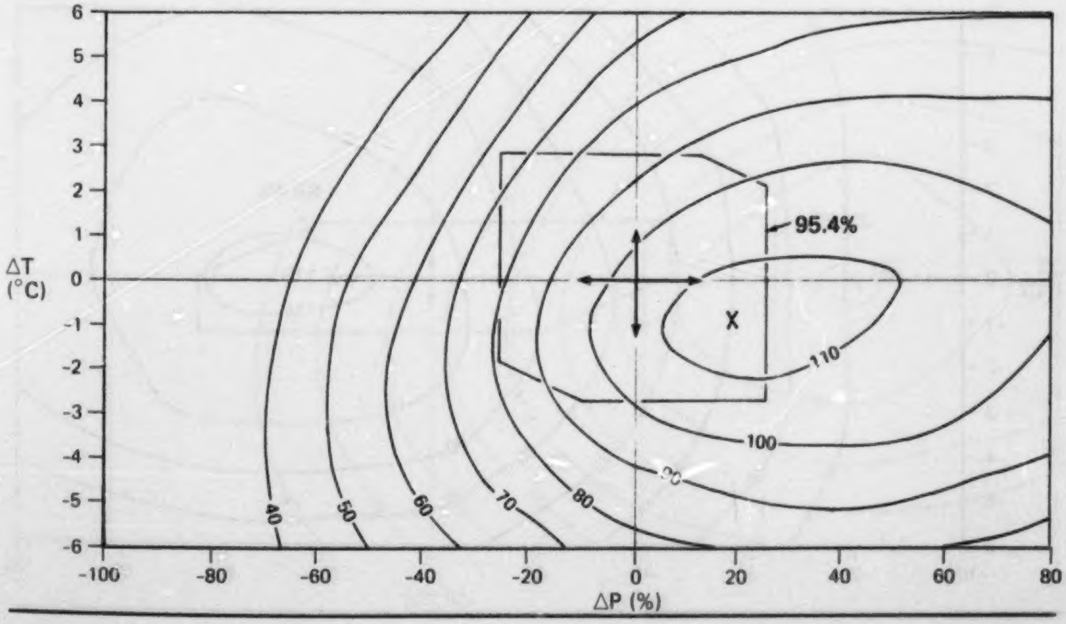


Figure V-3

RICE: *India*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

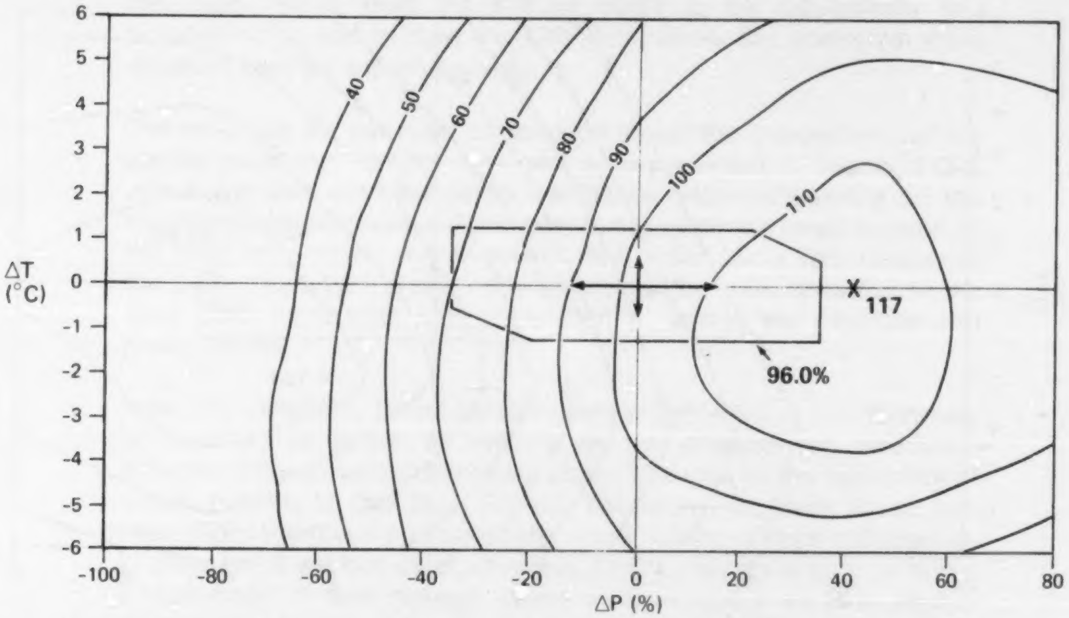


Figure V-4

RICE: *PRC*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

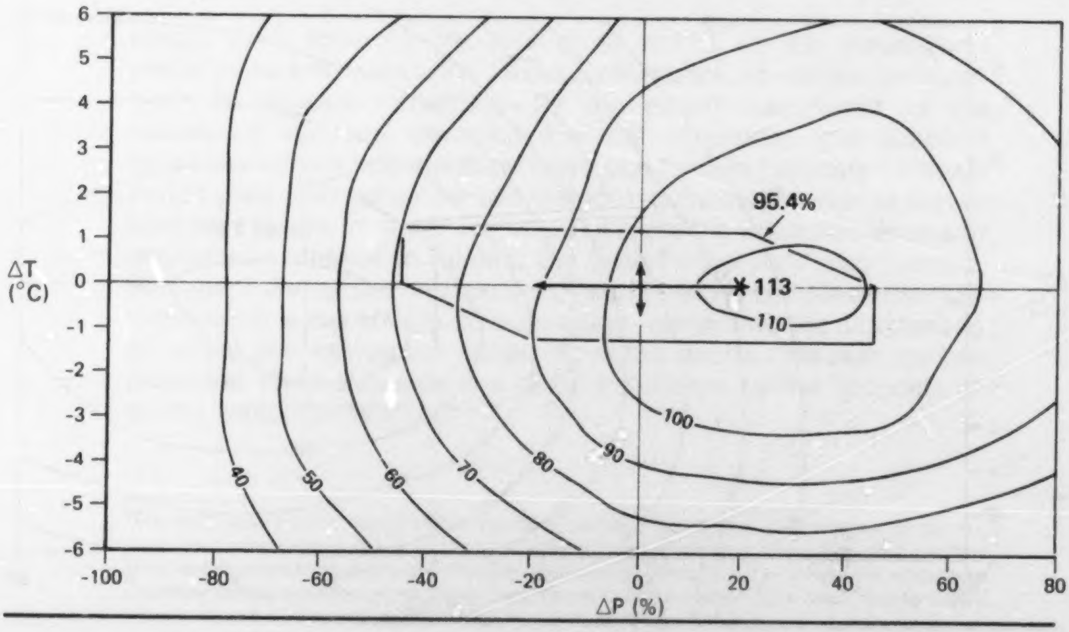


Figure V-5

SOYBEANS: *Brazil*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

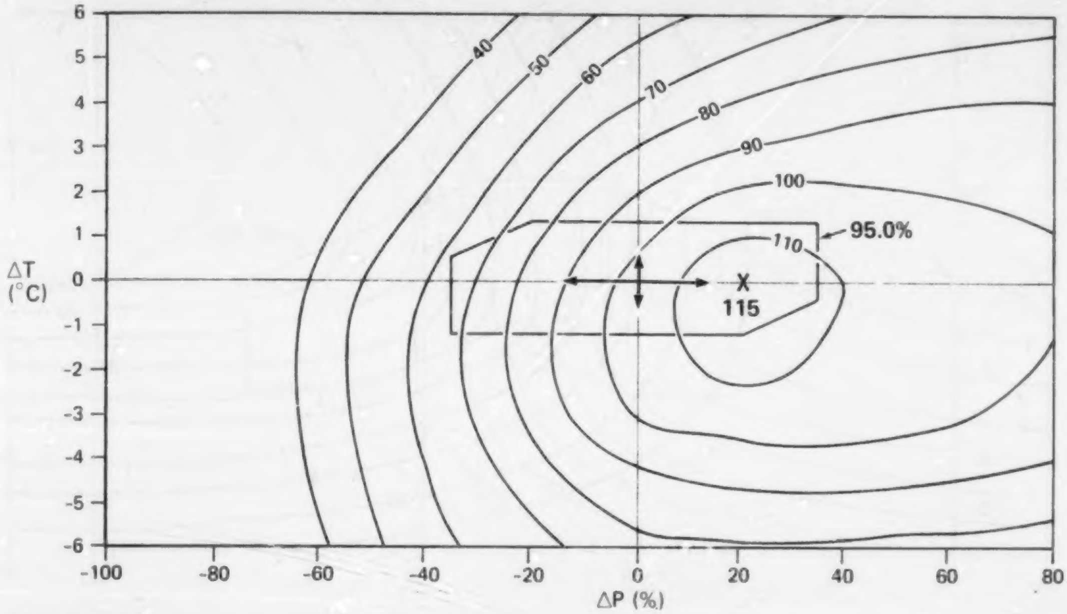


Figure V-6

SOYBEANS: *U.S.*
Annual-Yield Response Surface (100 = Base-Period Expected Yield)

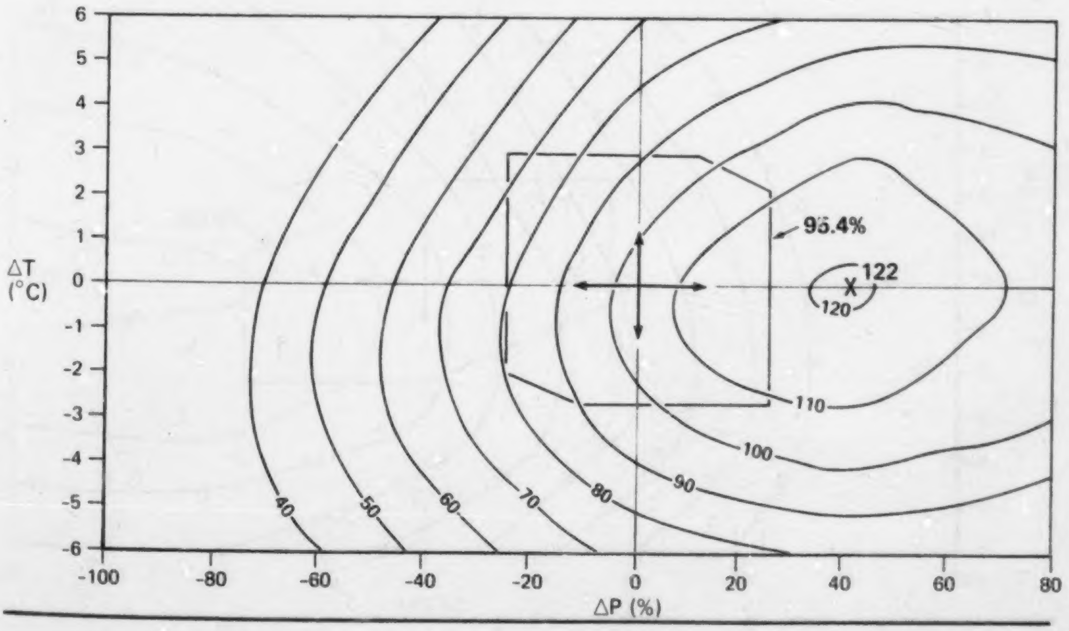


Figure V-7

SPRING WHEAT: *Canada*

Annual-Yield Response Surface (100 = Base-Period Expected Yield)

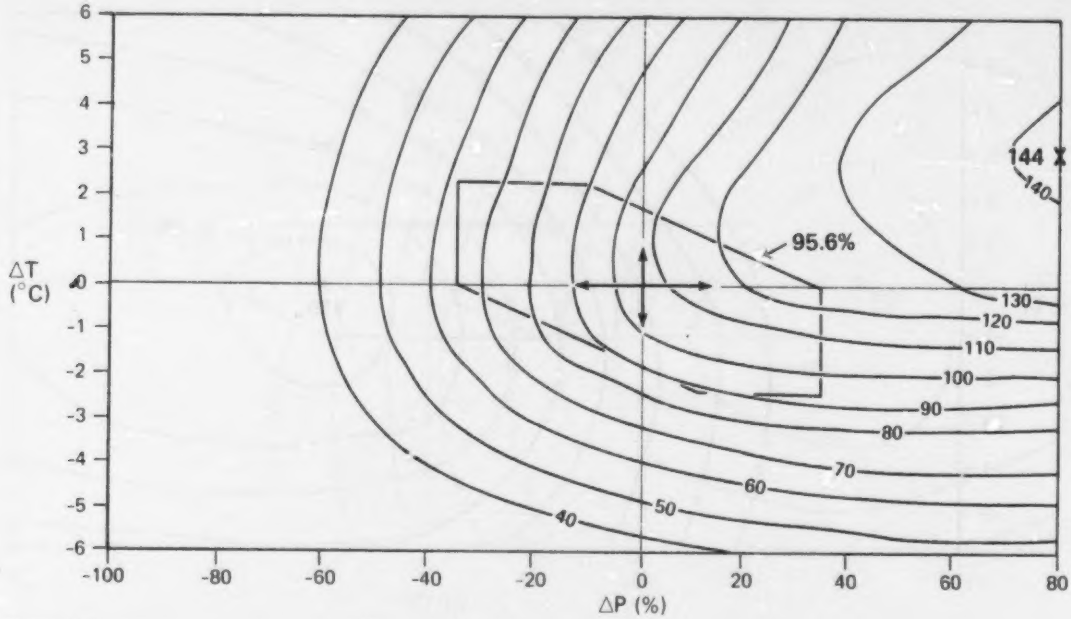


Figure V-8

SPRING WHEAT: *U.S.*

Annual-Yield Response Surface (100 = Base-Period Expected Yield)

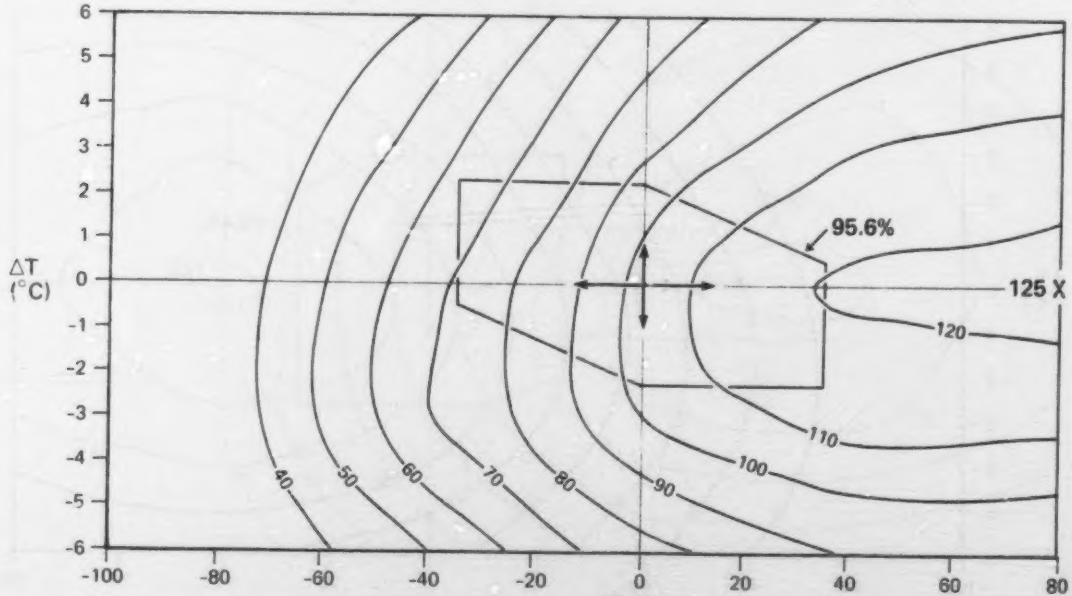


Figure V-9

SPRING WHEAT: ***USSR***

Annual-Yield Response Surface (100 = Base-Period Expected Yield)

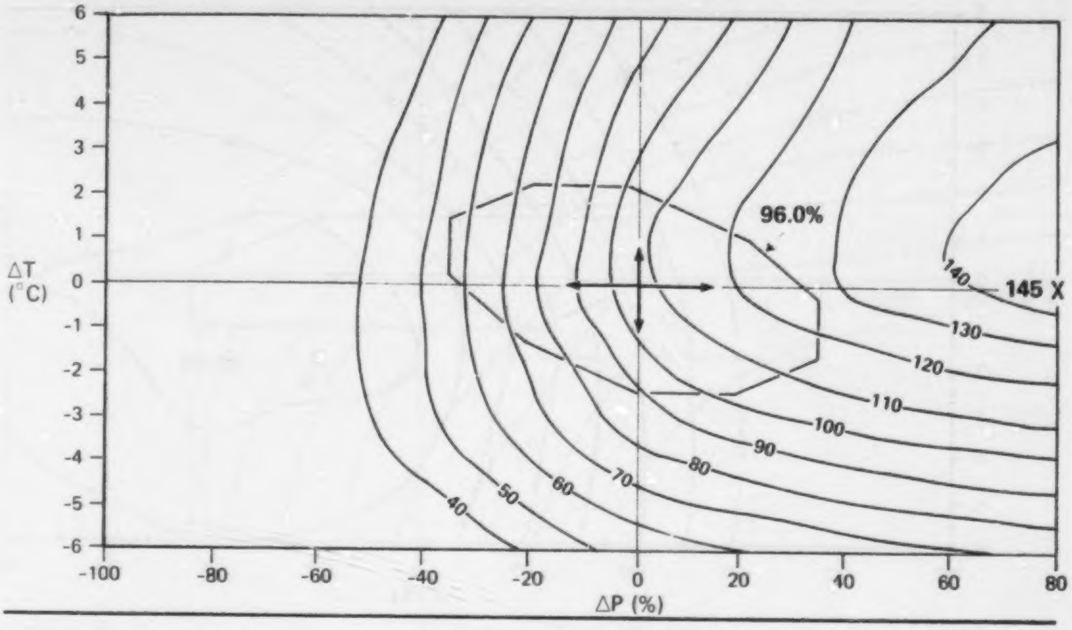


Figure V-10

WINTER WHEAT: *Argentina*

Annual-Yield Response Surface (100 = Base-Period Expected Yield)

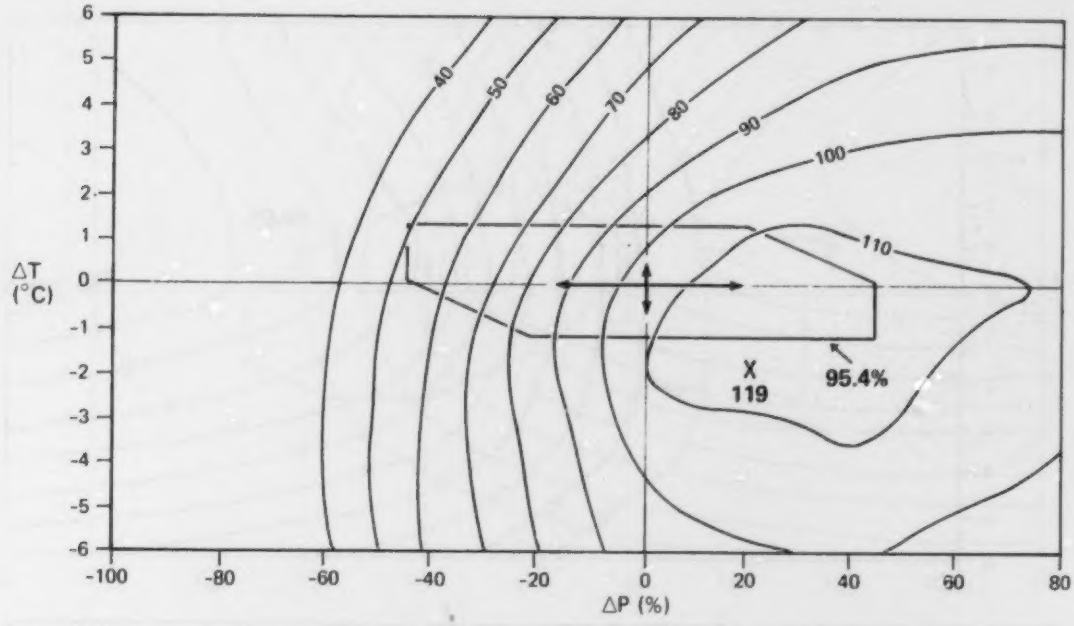


Figure V-11

WINTER WHEAT: *Australia*

Annual-Yield Response Surface (100 = Base-Period Expected Yield)

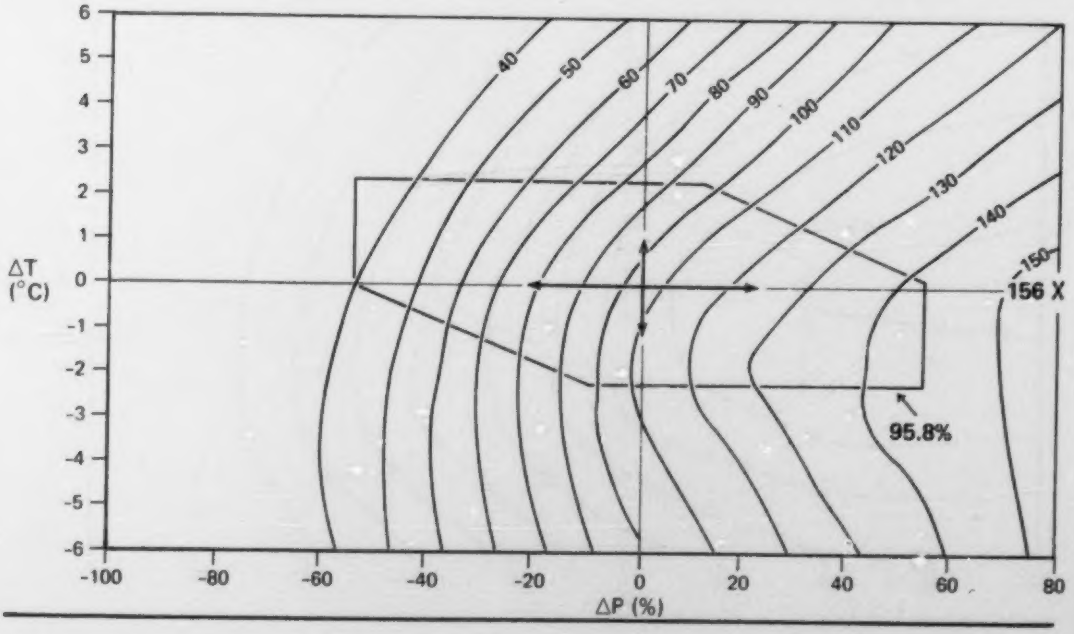


Figure V-12

WINTER WHEAT: *India*

Annual-Yield Response Surface (100 = Base-Period Expected Yield)

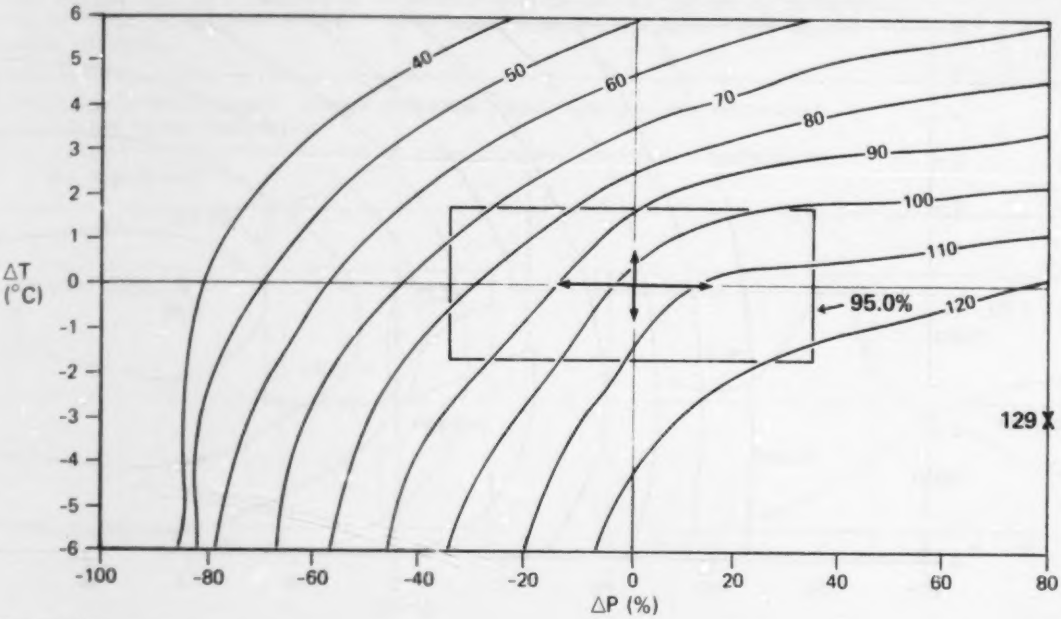


Figure V-13

WINTER WHEAT: *PRC*

Annual-Yield Response Surface (100 = Base-Period Expected Yield)

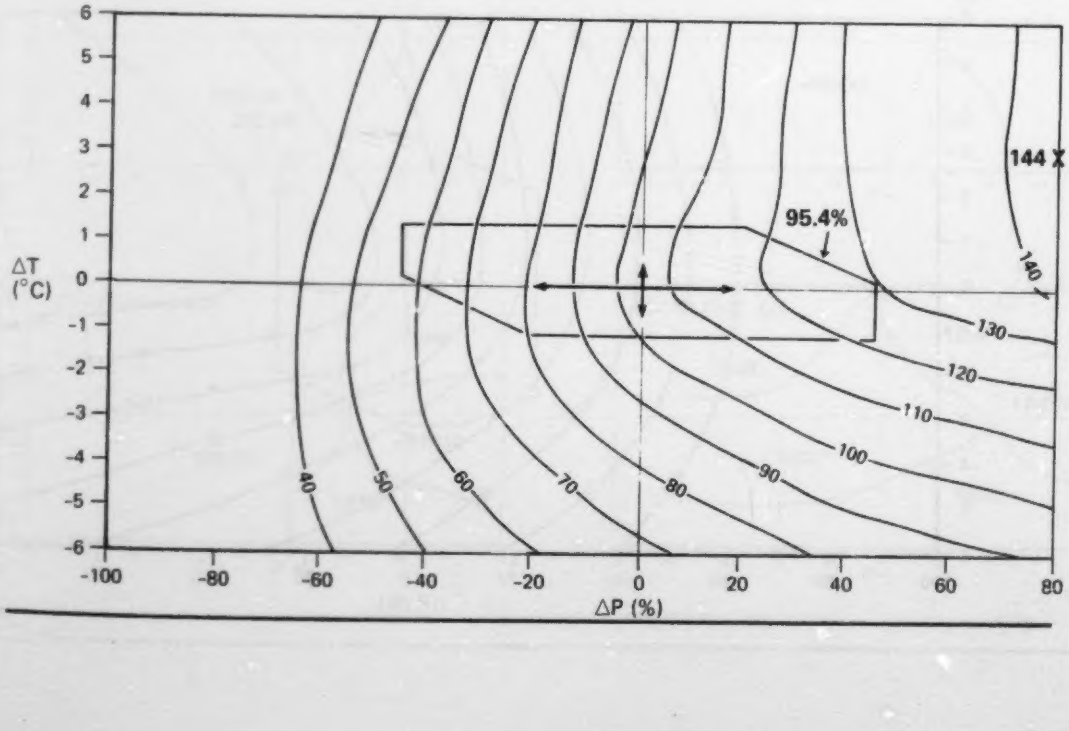


Figure V-14

WINTER WHEAT: *U.S.*

Annual-Yield Response Surface (100 = Base-Period Expected Yield)

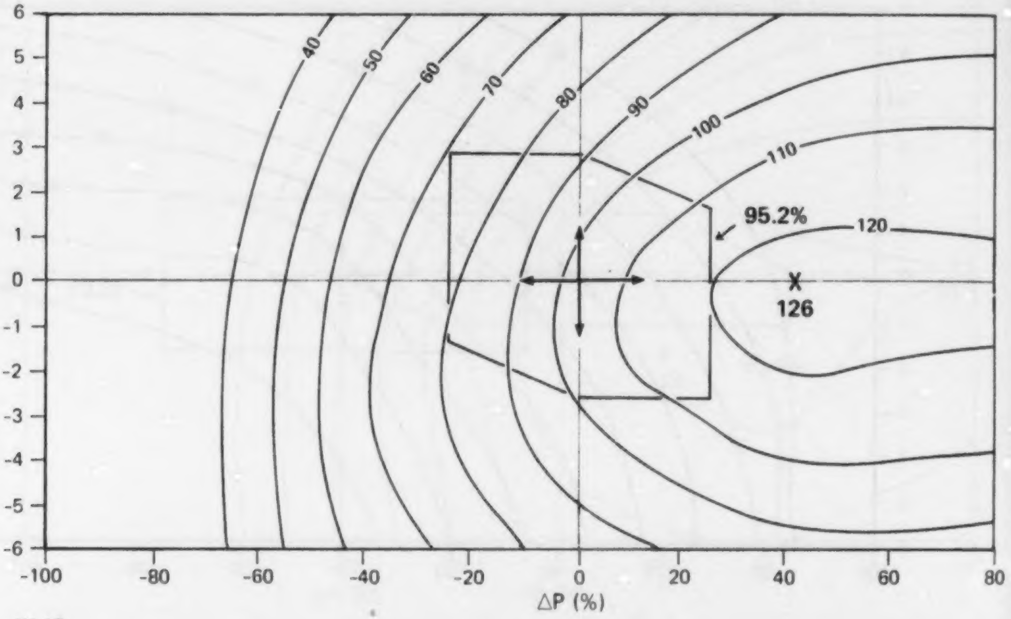


Figure IV-15

WINTER WHEAT: *USSR*

Annual-Yield Response Surface (100 = Base-Period Expected Yield)

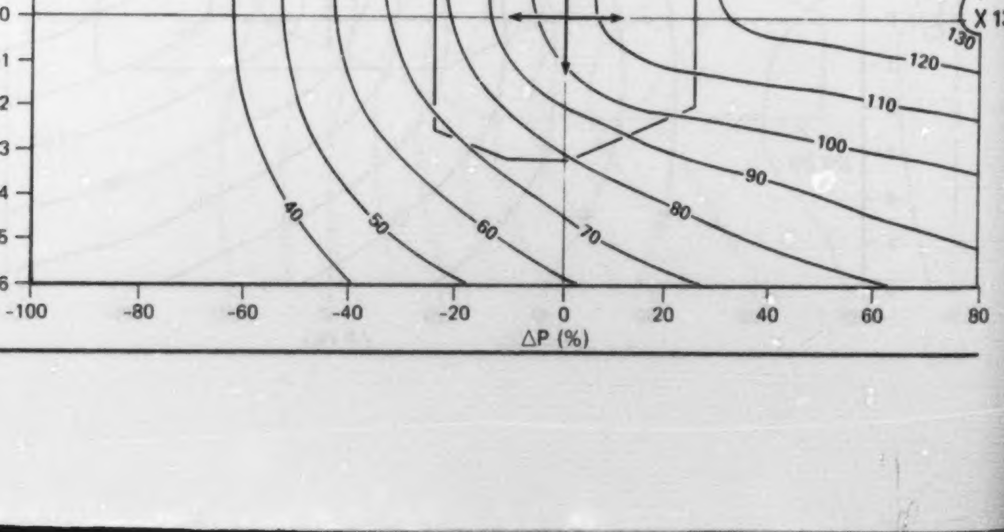


Figure V-16

THE RELATIVE INFLUENCE OF TEMPERATURE AND PRECIPITATION ON THE VARIABILITY OF YIELDS –– GLOBAL ANALYSIS

Climate changes ($\Delta\overline{T}$, $\Delta\overline{P}$) classified as to whether year-to-year fluctuations of temperature (TEMP or T) or precipitation (PRECIP or P) would have the dominant effect on the variability of yields.

$\Delta\overline{T}$ = change in the long-term average of annual mean heading-period temperature reffered to the Base-Period.

$\Delta\overline{P}$ = change in the long-term average of mean crop-year precipitation reffered to the Base-Period.

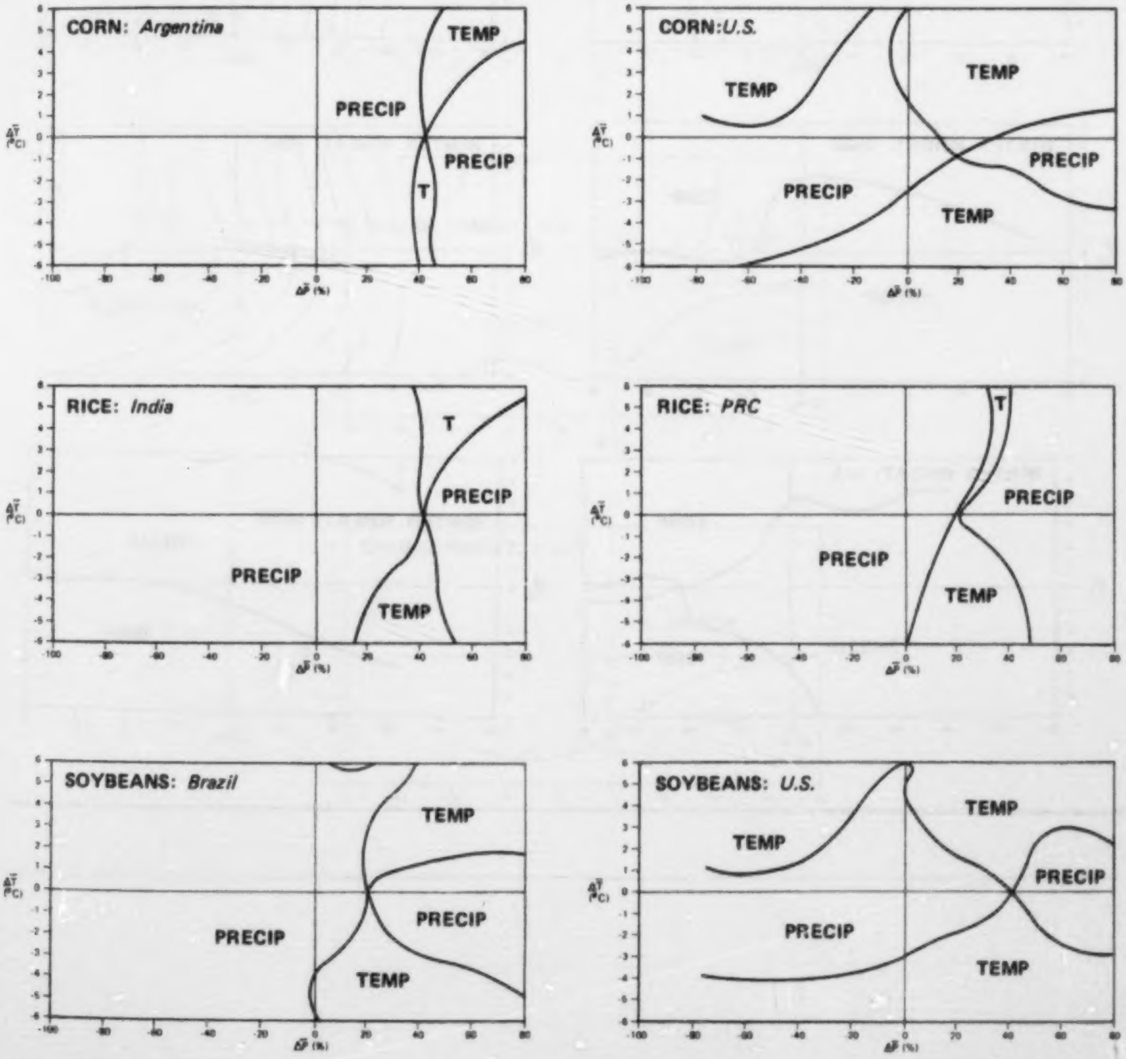


Figure V-16 (cont.)

THE RELATIVE INFLUENCE OF TEMPERATURE AND PRECIPITATION ON THE VARIABILITY OF YIELDS -- GLOBAL ANALYSIS

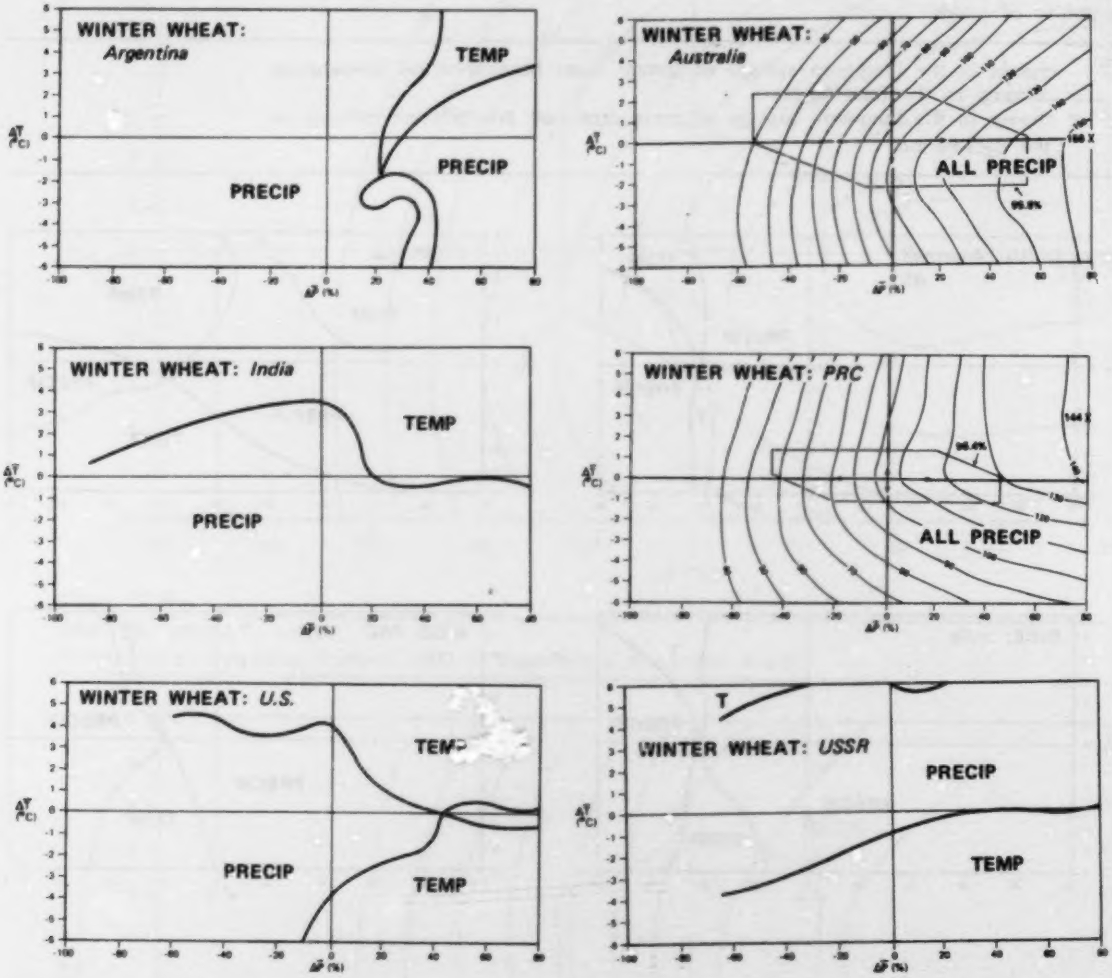


Figure V-16 (cont.)

THE RELATIVE INFLUENCE OF TEMPERATURE AND PRECIPITATION ON THE VARIABILITY OF YIELDS –– GLOBAL ANALYSIS

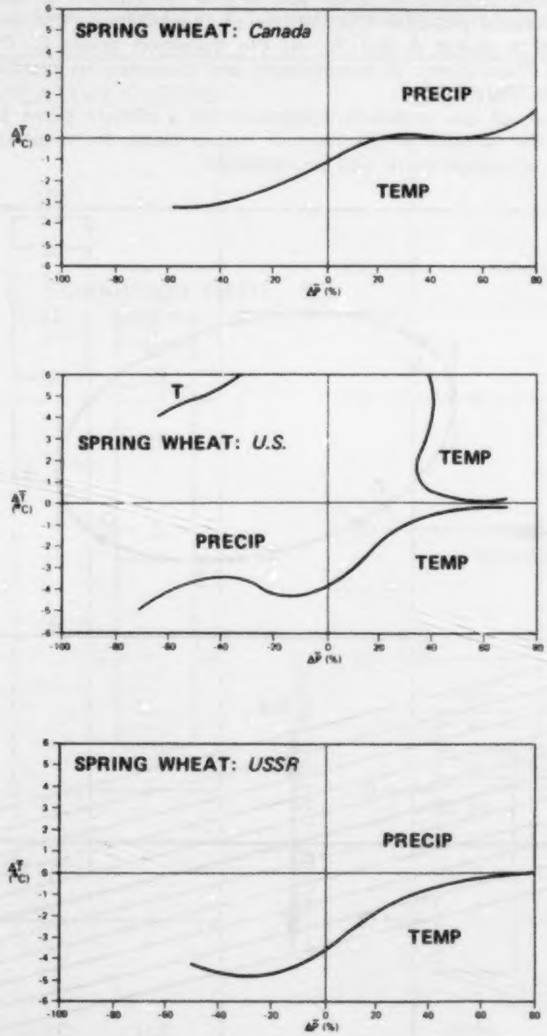


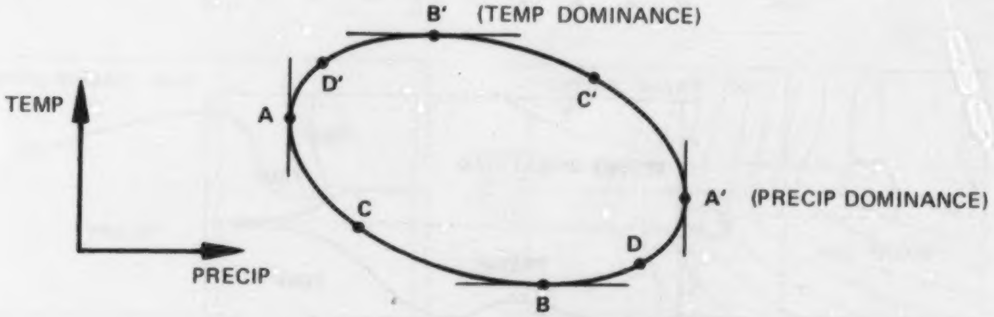
Figure V-17

GEOMETRIC BASIS OF THE GLOBAL SENSITIVITY ANALYSIS

Part A shows the climate points B and B′ on a yield contour curve at which annual yields would be most sensitive to small year-to-year fluctuations of temperature and least sensitive to equally probable fluctuations of precipitation; the reverse of these sensitivities prevails at points A and A′. At the transition points C, C′, D and D′ small equiprobable fluctuations of temperature and precipitation produce yield changes of equal magnitude. PartB

Part B illustrates on of the sufficient conditions for a climate point to be at a transition point: at C the tangent to the contour has as slope the negative ratio of the standard deviation of temperature and precipitation.

PART A



PART B

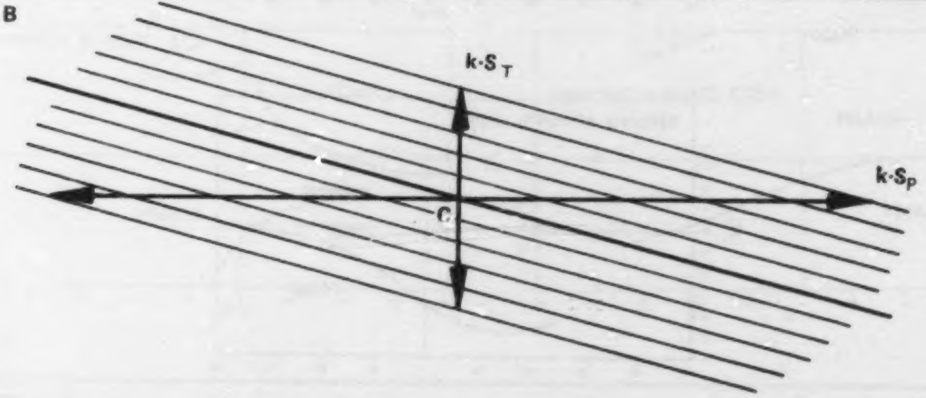


Figure V-18

COMPARISONS OF RELATIVE AND ABSOLUTE YIELD DISTRIBUTIONS — ARGENTINE CORN AND U.S. CORN IN THE BASE PERIOD

The solid horizontal divisions in the vertical bars mark the percentiles of yield. The dashed horizontal divisions mark the expected values of the yield distributions. The 1976 linear trend values were taken as the absolute equivalents of the expected relative yields.

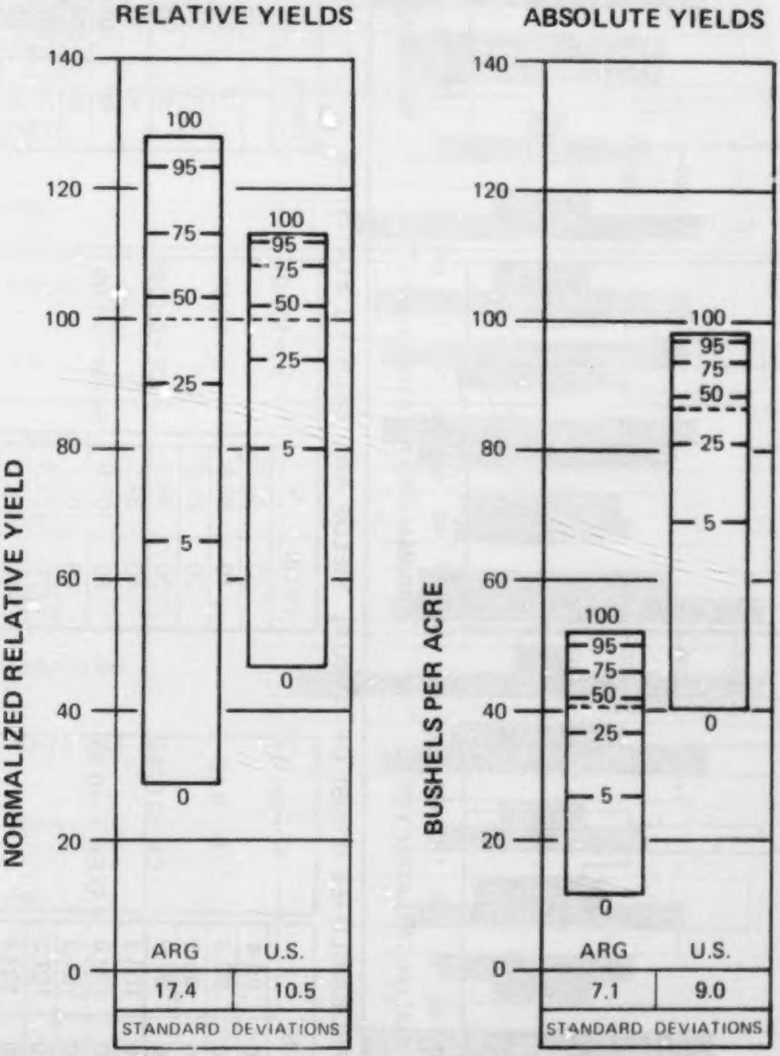
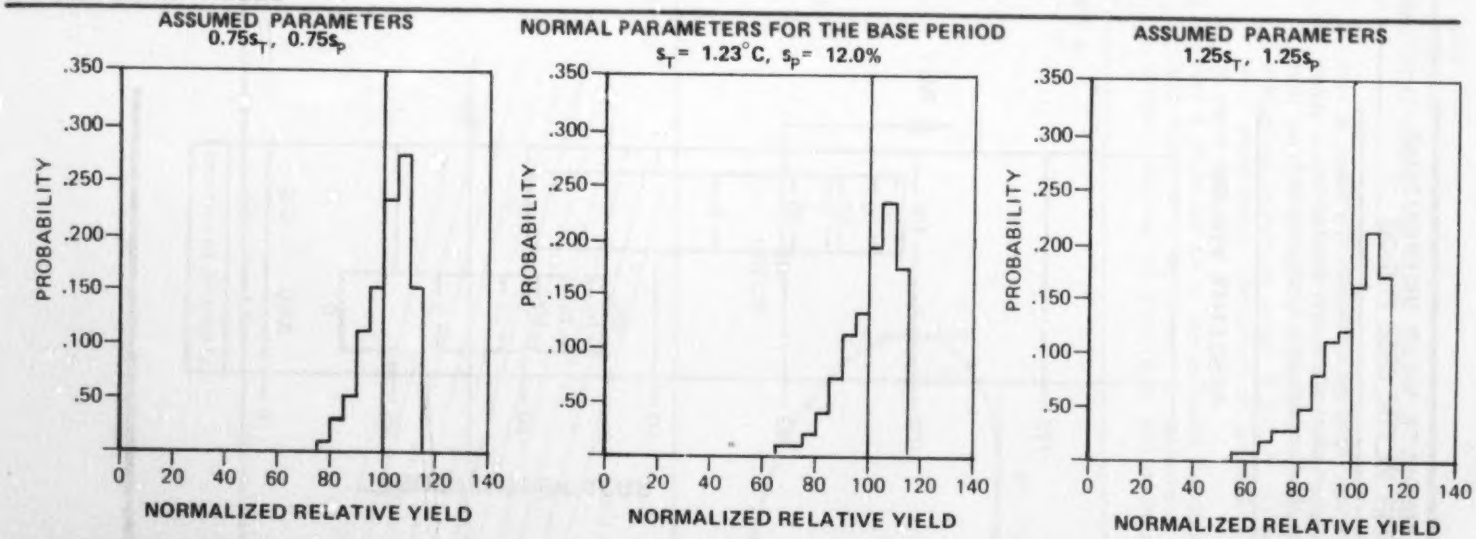


Figure V-19

EFFECT OF 25% CHANGES IN THE BND PARAMETERS s_T, s_p ON THE BASE–PERIOD DISTRIBUTION OF U.S. CORN YIELDS


ASSUMED PARAMETERS $0.75s_T$, $0.75s_p$

NORMAL PARAMETERS FOR THE BASE PERIOD s_T = 1.23°C, s_p = 12.0%

ASSUMED PARAMETERS $1.25s_T$, $1.25s_p$

CUMULATIVE PROBABILITIES (PROB) OF ANNUAL YIELDS AND RELATED STATISTICS

PROB	$\overline{Y}$
0	60.4
10	90.3
20	95.0
30	97.9
40	100.7
50	102.9
60	105.3
70	107.3
80	108.9
90	111.3
100	113.2

$\overline{Y}$ = 101.71

S = 8.10

CV = 0.0796

SKEW = −0.89

PROB	$\overline{Y}$
0	46.5
10	85.6
20	91.8
30	96.2
40	99.5
50	102.0
60	105.1
70	107.3
80	109.2
90	111.5
100	113.2

$\overline{Y}$ = 100.01

S = 10.46

CV = 0.1046

SKEW = −1.09

PROB	$\overline{Y}$
0	35.4
10	80.1
20	88.0
30	93.3
40	97.5
50	101.1
60	104.2
70	107.0
80	109.2
90	111.5
100	113.2

$\overline{Y}$ = 97.96

S = 12.79

CV = 0.1306

SKEW = −1.17

$\overline{Y}$ = Expected Value, S = Standard Deviation, CV = Coefficient of Variability, SKEW = Skewness

Figure V-20

EFFECT OF 25% CHANGES IN THE BND PARAMETERS s_T, s_P ON AVERAGE YIELDS

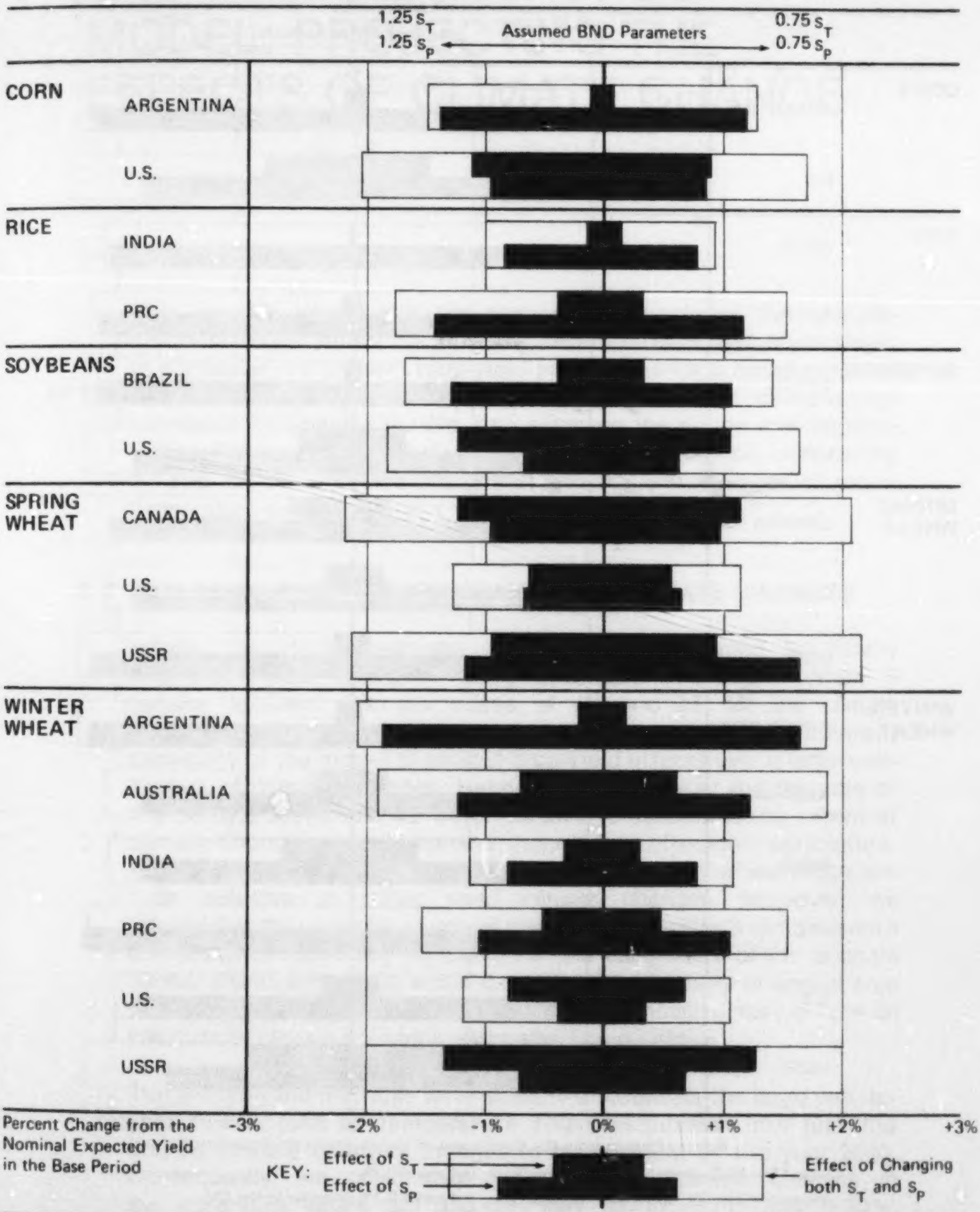
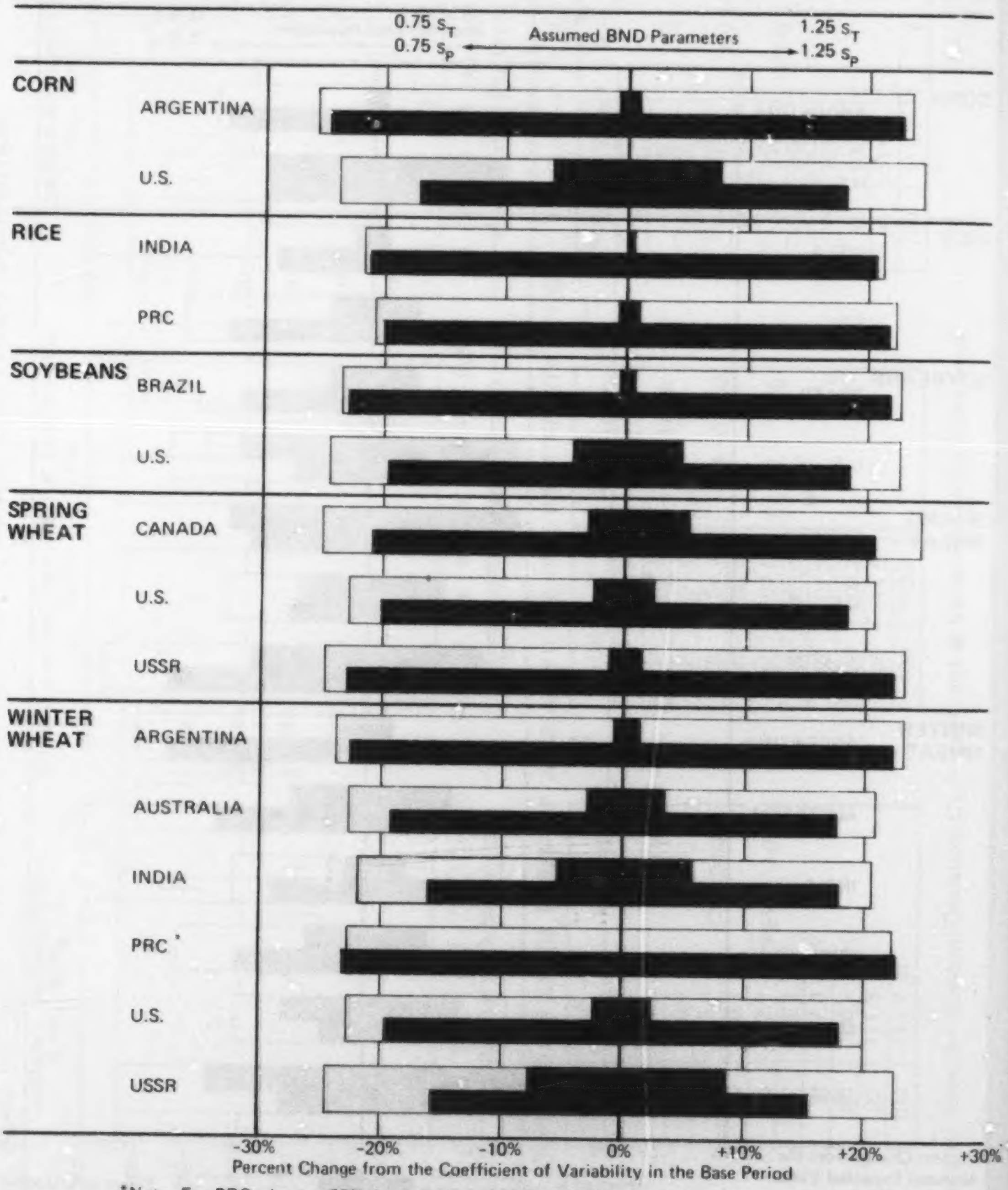


Figure V-21

EFFECT OF 25% CHANGES IN THE BND PARAMETERS ON THE VARIABILITY OF ANNUAL YIELDS



*Note: For PRC wheat, a 25% decrease in s_T induces a 0.2% increase in the CV, and a 25% increase in s_T induces a 0.1% decrease in the CV.

CHAPTER SIX
THE CLIMATE-RESPONSE MODEL: PROJECTING THE EFFECTS OF CLIMATE CHANGE

6-1 INTRODUCTION

This chapter deals with the predictive aspects of the climate-response model under the standing assumption of 1976 technology. In particular, we present crop-yield projections for a broad range of climatic change, thus providing a context for the climate-crop scenarios of Chapter III. We also examine the scope and implications of the uncertainty in the five climate scenarios concerning $\Delta\bar{T}$ and $\Delta\bar{P}$, the expected changes in the long-term averages of annual temperature and precipitation.

6-2 EXPLORING THE EFFECTS OF EXTREME CLIMATE CHANGES

Initially, the climate-response model was programmed to handle only the climate scenarios being developed in Task I. When it became apparent that the values of ΔT and ΔP for the climate scenarios would be quite modest, we decided to exploit the inherent capability of the model to project crop-yield effects over a large continuum of climate changes. Hence, no matter what the impacts of the climate scenarios, we would be able to determine the extent of climate change needed to product significant effects on agriculture. As it turned out, the model indicates that some key wheat crops are quite sensitive to rather small climate changes. Moreover, we learned that the variability of annual yields can change with climate even if one assumes essentially no change in the parameters of the bivariate normal distribution (BND) which describes the variability of annual crop weather. And, of course, we wound up with a synoptic picture of how an infinitude of climate scenarios might affect crop yields.

The annual-yield matrices were sized to account for the large year-to-year fluctuations of temperature and precipitation, not just the limited climate changes thought to be possible by the year 2000. Consequently, we could map the effects of climate changes in the continuum where $\Delta\bar{T}$ and $\Delta\bar{P}$ vary up to ±3°C and ±30%.

These boundary values strain the credibility of the model in two ways. First, the validity of the Base-Period BND parameters becomes more questionable as the magnitudes of $\Delta\overline{T}$ and $\Delta\overline{P}$ increase. Second, if the climate shift is too large, portions of the BND matrix will fall outside the annual-yield matrix. Therefore, the distribution of annual yields calculated for an extreme climate change may fail to account for some fraction of annual yields. However, within this particular climate-change continuum, such "missing" fractions are small because they correspond to annual crop-weather events of very low probability. Instead of extrapolating the annual-yield matrices to accommodate the translated BND matrices, we chose to maintain a record of the "missing" BND probabilities by keeping track of the "total probability" of the annual yields that *are* accounted for, i.e, the sum of the BND probabilities that lie within the borders of the annual-yield matrix.

By way of a reconnaissance of the climate-change continuum, we calculated frequency distributions of annual yields pertaining to the nine climate states for which $\Delta\overline{T}$ and $\Delta\overline{P}$ independently assume values of −3°, 0°, +3°C and −30%, 0%, +30%. The results are displayed in Appendix E-1 as arrays of histograms. As explained in the next section, the distribution with the minimum expected yield for the entire climate continuum always lies in either the upper or the lower left-hand corner of an array, but the array is unlikely to include the climate change with maximum expected yield. Even so, the histograms exhibit a wide variety of shapes, despite the fact that the same pattern of year-to-year fluctuations in crop weather was assumed for all climate states.

6-3 THE EXPECTED-YIELD SUMMARY TABLES

For a more detailed investigation of the climate-change continuum we established a regular 7x7 lattice of points in the $\Delta\overline{T}$, $\Delta\overline{P}$-plane. At each of the 49 lattice points we calculated the following data:

- The expected value and the standard deviation of normalized relative annual yields.
- The skewness of the yield distribution.
- The "total probability" mentioned in the preceding section.

These data are presented in the Expected-Yield Summary Tables of Appendix E-2.

An Expected-Yield Summary Table will always include the minimum value assumed by the expected-yield function in the climate-change continuum, but generally it will not include the maximum value. From the nature of the annual-yield response surfaces (Figures V-1 through V-15), it can be seen that the *minimum* expected yield in the continuum will occur when $\Delta\bar{P} = -30\%$ and when either $\Delta\bar{T} = -3°C$ or $\Delta\bar{T} = +3°C$. Therefore, the smaller of the two expected yields in the upper and lower left-hand corners of an Expected-Yield Summary Table will not only be the smallest entry in the table but it will also be the minimum expected yield for the continuum. The location of this minimum is shown in Table VI-1. On the other hand, it can only be said that a given crop's *maximum* expected yield for the continuum will occur somewhere on or close to the line $\Delta\bar{P} = +30\%$. Hence it is unlikely that the maximum yield will correspond exactly to one of the lattice points. The location of the largest tabulated expected yield, which can be slightly smaller than the maximum for the continuum, is also shown in Table VI-1.

Relative to the climate-change continuum, Table VI-1 indicates that:

- Expected yields can drop as much as 50% below the Base-Period value of 100, but the potential increases in expected yields are much more limited—20% or less for 11 of the key crops.
- The expected yields of four northerly wheat crops respond most favorably to a warmer, wetter climate and least favorably to a cooler, drier climate. (Their largest expected yields occur for positive $\Delta\bar{T}$ and their smallest for $\Delta\bar{T} = -3°C$.)
- Generally, the expected yields of the remaining key crops respond most favorable to a cooler, wetter climate and least favorably to a warmer, drier climate.
- Annual yields are more variable for the most adverse climate change than for the most benign climate change (according to either the standard deviations in the table or the corresponding coefficients of variability[1]).

From a perusal of the Expected-Yield Summary Tables themselves, one notes the following:

- Except for climate changes with very low expected yields, the yield distributions are negatively skewed, i.e., the longer tails of the distributions extend toward the lower yields.
- As indicated by the "total probabilty" entries, the "missing" fractions of the yield distributions for the more extreme climate changes exceed 0.022 only in the case of Australian wheat.
- For ten key crops, no "missing" fraction exceeds 0.009.

6-4 RESPONSE SURFACES FOR THE EXPECTED VALUES AND STANDARD DEVIATIONS OF ANNUAL YIELDS

Using the same procedures by which the annual-yield response surfaces were derived from the Master Yield Grids, we developed two climate response surfaces from each Expected-Yield Summary

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[1] The ratios of the standard deviations to the respective expected values.

Table VI-1

SMALLEST AND LARGEST EXPECTED YIELDS IN THE EXPECTED YIELD SUMMARY TABLES

Crop and Country	Smallest Expected Yield ($\Delta\overline{P}$=-30%)			Largest Expected Yield ($\Delta\overline{P}$=+30%)		
	$\Delta\overline{T}$	$\overline{Y}$	S_Y	$\Delta\overline{T}$	$\overline{Y}$	S_Y
CORN						
ARGENTINA	+3	52.8	14.0	-1	119.2	10.5
U.S.	+3	59.2	12.5	-1	108.5	4.4
RICE						
INDIA	+3	66.6	9.5	-1	111.9	5.0
PRC	+3	53.0	8.5	-1	105.6	7.2
SOYBEANS						
BRAZIL	+3	53.0	8.5	-1	109.1	4.2
U.S.	+3	61.5	10.6	0	113.2	6.2
SPRING WHEAT						
CANADA	-3	52.7	7.0	+2	122.6	10.6
U.S.	+3	63.8	9.3	0	115.0	6.7
USSR	-3	55.0	8.3	+1	123.6	11.0
WINTER WHEAT						
ARGENTINA	+3	55.3	12.3	-1	111.8	7.1
AUSTRALIA	+3	50.0	18.7	-2	127.1	20.2
INDIA	+3	59.4	9.3	-3	122.2	6.1
PRC	-3	66.4	8.8	+1	119.9	16.0
U.S.	+3	66.0	7.6	-1	117.2	5.9
USSR	-3	60.9	10.3	+2	117.4	6.1

Table (see Figures VI-1 through VI-15). One, the expected-yield response surface, is concerned with the effect of climate change on the *average* annual yield. The other, the standard-deviation response surface, deals with the effect of climate change on the variability of annual yields. In both contour plots, the origin (no climate change) represents the Base Period.

In the case of Argentine corn (Figure VI-1), for example, a climate one degree warmer ($\Delta\bar{T} = +1.0°C$) and 20% wetter ($\Delta\bar{P} = +20\%$) than the "present" results in a projected expected yield of about 110. That is, the temporally averaged yield is 10% greater than in the Base Period. The standard deviation of Argentine corn yields corresponding to the same climate change is about 14.5, while it is somewhat larger than 17 in the Base Period. Thus, for this assumed climate regime it is projected that normalized relative annual yields of Argentine corn would be less variable, and larger on the average, than in the Base Period (assuming the persistence of current technology).

The expected-yield response surfaces have the same general shapes as the respective annual-yield response surfaces in Figure V-1 through V-15. This is a direct consequence of the way the expected-yield surfaces were derived by shifting the BND matrices on the annual-yield matrices.

The relationship between the slopes of a pair of climate response surfaces also reflects their derivation. Consider, for example, the path of steepest *ascent* from the origin on an expected-yield surface. For most crops, the standard deviation of yields decreases along this path.[2] Indeed, for about half the key crops, the path of steepest *ascent* on the expected-yield surface and the path of steepest *descent* on the standard-deviation surface are almost coincident. (Canadian spring wheat and Chinese winter wheat are the most notable cases where the two paths diverge.) On the other hand, consider the path of steepest *descent* from the origin on an expected-yield surface. Along this path, most of the standard-deviation functions increase initially, reach a maximum, and then decrease.[3] (Again, Canadian spring wheat and Chinese winter wheat are exceptions; their standard deviations decrease monotonically along the path of most rapidly decreasing expected yields.)

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[2] This slope relationship can be explained by the graphical method introduced in Appendix D-3. Namely, as the BND polygon is moved "uphill" from the origin of the annual-yield surface, it encounters the relatively flat region where yields are less sensitive to fluctuations of annual temperature and precipitation than they are in the vicinity of the origin.

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[3] The initial increase in the standard deviation is due to the motion of the BND polygon "downhill" toward the steeper intermediate slopes of the annual-yield surface. The onset of decreasing standard deviations occurs as the BND polygon descends further to the region of lower yields, the "lip" of the bell-shaped annual-yield surface where the slopes approach zero.

The climate response surfaces have some common features with respect to changes in the long-term average of precipitation. If $\Delta\overline{T}$ is held constant and ΔP allowed to increase from −30% to +30%, we note that:

- The expected yield increases monotonically; hence more precipitation always favors higher average yields in this climate-change continuum.
- Except for Canadian wheat, the standard deviation increases at first and then levels off or decreases; hence the standard deviation has a maximum at some intermediate value of $\Delta\overline{P}$ (usually a negative value).

The key crops exhibit a variety of behavior with respect to $\Delta\overline{T}$. In only one case can one make an unqualified statement about the effect of $\Delta\overline{T}$ for a fixed value of $\Delta\overline{P}$: a higher temperature always depresses the average yield of Indian wheat.

6-5 SUPERPOSITION OF THE FIVE CLIMATE SCENARIOS ON THE CLIMATE RESPONSE SURFACES

The main objective of Task II was to project the likely responses of the 15 key country-crop combinations to the five global climate scenarios that were developed in Task I, but the general methodology devised for this purpose enables one to construct abbreviated climate-crop scenarios at will. One simply concocts a global climate scenario in sufficient detail to specify $\Delta\overline{T}$ and $\Delta\overline{P}$ for each country-crop combination. The expected values and standard deviations of annual yields can then either be read directly from Figures VI-1 through VI-15 or interpolated with more precision from the Expected-Yield Summary Tables. In addition, the skewness of the yield distributions may be derived from the summary tables.

The expected values of $\Delta\overline{T}$ and $\Delta\overline{P}$ which determines the effects of the five climate scenarios are listed in Table S-1 and plotted on Figures VI-1 through VI-15 with "+" symbols. To illustrate the types of information available from the superposition of the five climate scenarios on the climate response surfaces, we make some observations about Argentine corn (Figure VI-1).

- In the three warming scenarios, expected yields are lower, and standard deviations are slightly higher, than in the Base Period.
- In the Large Warming Scenario, the warming *per se* ($\Delta\overline{T} = +1.0°C$) tends to depress yields, but this negative effect is partially offset by the enhancing effect of the expected increase in precipitation ($\Delta\overline{P} = +2.0\%$).
- In the two cooling scenarios, the expected yields of Argentine corn increase from the Base-Period value, while the standard deviations

of yield decrease slightly.

- In the Large Cooling Scenario, the changes in temperature ($\Delta\overline{T} = -0.95°C$) and precipitation ($\Delta\overline{P} = +2.0\%$) reinforce each other to increase the expected yields.

The climate response surfaces provide only the expected value and standard deviation of the projected frequency distribution of normalized relative annual yields. In Figure VI-16 we show how the actual distributions of U.S. corn yields differ from scenario to scenario. The differences among the distributions are not so pronounced as they are for the more radical climate changes addressed in Appendix E-1. Nor do the distributions in Figure VI-16 differ as much as they would for the Canadian and Soviet wheat crops, which are considerably more sensitive to global temperature changes than U.S. corn.

The negative skewness seen in Figure VI-16 is a common property of all the key crops in the same six climate states. In the passage from the lowest to highest global temperature (left to right in the first row and right to left in the second) there is a regular transition in the statistics and shapes of the histograms. For example, the expected yield decreases, while the skewness and coefficient of variability increase. Thus, the U.S. corn distributions differ most between the Large Cooling and Large Warming Scenarios.

For additional material on yield distributions, see the discussion in Section 4-4 about the comparative variability of annual yields in the Base Period and the two extreme climate scenarios. That discussion was based on coarse frequency distributions of annual yields expressed as fractions of the expected yields peculiar to each of the three climate states.

6-6 THE RANGES OF UNCERTAINTY IN THE CLIMATE SCENARIOS

The "probabilities" of the five global climate scenarios reflect the climate panelists' diverse perceptions about the course of *global* temperature to the year 2000. Within each scenario, the aggregated probability distributions of zonal temperature and precipitation changes indicate further uncertainty about even gross details of global climate change (see Tables III-1A through III-5A). In Chapters III and IV, the projected effects of a climate scenario were based on the *expected values* of $\Delta\overline{T}$ and $\Delta\overline{P}$ for each latitude zone. Therefore, the "canonical" climate-crop scenarios do not account for the panelists' uncertainty about zonal climate changes. However, as outlined in Chapter I, we kept track of the effects of this uncertainty on expected crop yields. We shall examine the scope of climatic uncertainty affecting one zone of latitude and then give algorithms that enable one to analyze the uncertainty for the remaining latitude zones. The agricultural implications of the climatic uncertainty are considered in the next two sections.

The *combined* uncertainty about zonal temperature and precipitation changes in a given climate scenario is expressed by a table of joint and marginal probabilities, as in Table I-9. From this table, which pertains to the northern lower middle (N-LM) latitudes, it appears that the Large Warming Scenario "occupies" a large region in the $\Delta\overline{T}$, $\Delta\overline{P}$-plane. Taking Table I-9 literally, one has to say that in large warming the average annual temperature of the N-LM latitudes could be almost 0.25°C *cooler* than at present or almost 2.25°C *warmer*, while average annual precipitation could differ by as much as ±22.5% of the present value.

The envelope of the values of $\Delta\overline{T}$ and $\Delta\overline{P}$ which are ostensibly possible for the N-LM latitudes in the Large Warming Scenario is shown in Figure VI-17, along with envelopes of the other global climate scenarios. Also plotted are the expected climate changes which serve as proxies for all the climate changes within their respective envelopes. Figure VI-17 applies to U.S. corn and the other key crops of the N-LM latitudes.

In Appendix E-3 we discuss how the methodology contributed to some of the uncertainty suggested by Figure VI-17. We think the uncertainty about temperature change could have been reduced somewhat, although such a reduction by itself probably would not alter the yield projections very much. The climate panelists' uncertainty about precipitation, which has a stronger effect on yields, appears to be more deeply rooted and less amenable to reduction.

Instead of reproducing all the analogs of Table I-9, we now give general rules for finding the marginal probabilities that determine the scope of uncertainty about zonal climate change. We deal first with the uncertainty about $\Delta\overline{T}$, the change in average annual temperature. The original projected distributions of $\Delta\overline{T}$ had to be modified slightly to make them compatible with the climate-response model. The modification, which consists of a simple shift in temperature cells, is illustrated in Table VI-2 for the case of the N-LM latitudes in the Large Warming Scenario. In Task I the temperature cells were centered on odd integral multiples of 0.25°C. The aggregated probabilities attributed to the original temperature cells have been transcribed from Table III-5A (large warming) to the first row of Table VI-2. The modified distribution is shown in the second row of temperature cells, which are centered on integral multiples of 0.50°C. The probability associated with one of the shifted cells in the second row is the average of the probabilities in the two first-row cells which overlap it. The expected values of the

Table VI-2

PROBABILITIES OF TEMPERATURE CHANGES ($\Delta\overline{T}$) FOR THE NORTHERN LOWER MIDDLE LATITUDES IN THE LARGE WARMING SCENARIOS

$\Delta\overline{T}$ in Degrees Celcius

	-0.25°	0.25°	0.75°	1.25°	1.75°	2.75°
Probability Distribution from Table III-6A	0.0	0.1	0.5	0.2	0.2	0.0

	0.0°	0.50°	1.0°	1.50°	2.0°
Marginal Probabilities of Temperature Change	0.05	0.30	0.35	0.20	0.10

$\Delta\overline{T}$ in Degrees Celcius

two temperature distributions are equal, of course: the common expected temperature change is $\Delta\overline{T} = +1.0°C$. The derived temperature distribution in the second row applies to all crops of the N-LM latitudes. It is the source of the marginal probabilities of temperature change affecting U.S. corn in the Large Warming Scenario (see Table I-9). By shifting temperature cells and averaging probabilities, one can construct the marginal probabilities of temperature change for any key crop in any climate scenario.

Next we consider the uncertainty about $\Delta\overline{P}$, the change in average annual precipitation. For each zone of latitude the climate panelists estimated the probabilities of change in annual precipitation, given certain changes in temperature.[4] The estimates were conditional probabilities that precipitation would: [1] increase by 10% or more, [2] change by less than 10%, and [3] decrease by 10% or more. The aggregated probabilities for these precipitation events are shown in Tables III-1A through III-5A. Since the three conditional probabilities sum to unity, they represent only two independent data: the cumulative probability for $\Delta\overline{P} < -10\%$ (the probability of event [3]) and the cumulative probability for $\Delta\overline{P} < +10\%$ (the sum of the probabilities for events [2] and [3]). Assuming an underlying *uniform* distribution, we derived from each pair of cumulative probabilities a frequency distribution for $\Delta\overline{P}$. The resulting frequency distributions are shown in Table VI-3, identified by the different combinations of the probabilities of events [1] and [3].

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[4] The climate panelists also estimated the probabilities of changes in "growing-season" precipitation. For the reasons stated in Section 5-2, we are interested here only in annual precipitation.

Table VI-3

KEY TO THE PROBABILITIES OF PRECIPITATION CHANGES ($\Delta\overline{P}$) FOR ALL LATITUDE ZONES AND ALL CLIMATE SCENARIOS

Identifying Probabilities		Expected Value of $\Delta\overline{P}$	Marginal Probabilities of $\Delta\overline{P}$ (percent) in Occurrences per Thousand							
$\Delta\overline{P}\geqslant 10\%$	$\Delta\overline{P}\leqslant -10\%$		-30%	-25%	-20%	-15%	SEE NOTE	+15%	+20%	+25%
0.2	0.2	0.0%	▨	▨	▨	125	150	125	▨	▨
0.2	0.3	-2.0%	▨	▨	112.5	125	125	125	12.5	▨
0.2	0.4	-5.0%	50	100	100	100	100	100	50	▨
0.3	0.2	+2.0%	▨	▨	12.5	125	125	125	112.5	▨
0.3	0.3	0.0%	▨	50	100	100	100	100	100	50
0.4	0.1	+6.0%	▨	▨	▨	37.5	125	125	125	87.5

Note: This column applies to $\Delta\overline{P}$=0%,±5%,±10%

Finding the marginal probabilities of precipitation changes for a particular latitude zone in a given climate scenario is a matter of selecting the appropriate row of Table VI-3. For example, suppose one is interested in the uncertainty affecting the N-LM latitudes in the Large Warming Scenario. One first turns to Table III-5A (large global warming) and reads the line for "lower mid-latitude": the probability of event [1] ($\Delta\overline{P} > +10\%$) is 0.3, and the probability of event [3] ($\Delta\overline{P} < -10\%$ is 0.2. The marginal probabilities can then be read from the fourth row of Table VI-3, which is identified by the probabilities 0.3 and 0.2 in the first and second columns, respectively. These are the marginal probabilities that appear in Table I-9. In the manner just illustrated, the uncertainty about zonal precipitation changes can be delineated for any of the global climate scenarios. Table I-9 and the other tables of joint probabilities were completed by multiplying pairs of marginal probabilities, i.e., $\Delta\overline{T}$ and $\Delta\overline{P}$ were assumed to be independent.

6-7 THE IMPLICATIONS OF CLIMATIC UNCERTAINTY: U.S. CORN IN THE LARGE WARMING SCENARIO

Having described the baggage of climatic uncertainty in our model, we now consider the implications of this uncertainty for one climate scenario and the projected average yield of one crop. In addition, to illuminate the methodology by which we tracked climatic uncertainty, we discuss the analogy between two yield distributions that were presented in Chapter I.

In the year 2000, each key crop will face a single climate state, not the smorgasbord of climate states implied by Figure VI-17. If all the unique states were known, our model should give a rather accurate account of changes in average annual yields due solely to the global climate change. Lacking this knowledge, we chose for each latitude zone in each climate scenario a "canonical" climate change determined by the expected changes in temperature and precipitation. The "expected" climate change was then used to calculate distributions of normalized relative annual yields for the crops grown in the zone. These canonical yield distributions are represented in Chapter III as "the" outcomes of a climate scenario. But our climate model is not all that determinate. One may interpret the model as follows: if the *global* temperature change should fall within the range, say, of the Large Warming Scenario, then nature would randomly pick a climate change for each latitude zone according to joint probabilities like those in Table I-9. Such choices could result in distributions of annual yields quite different from those attributed to large global warming in Chapter III. (This interpretation, of course, reflects human ignorance, not the physical world.)

Figure VI-18 indicates how the ostensible uncertainty about zonal climate changes might affect the average yield of U.S. corn. The expected climate changes for the two extreme climate scenarios are indicated by "+" symbols. In large warming, the expected normalized relative yield corresponding to the expected climate change is 97.5, and the associated standard deviation of annual yields is 11.7. Within the large-warming envelope, however, expected yields vary from a low of about 72 (with an approximate standard deviation of 13.5) to a high of about 107 (with standard deviation 5.8). Table I-9 implies that the large-warming temperature change for the northern lower middle (N-LM) latitudes is most likely to lie in a horizontal band which covers or passes near the expected climate change. But the clustering of temperature changes does not restrict the range of expected yields very much because our climate model, unrealistically, puts equal weight on precipitation changes between −17.5% and +17.5%.

According to Table I-9, the large-warming temperature change will lie within the horizontal shaded band in Figure VI-18 with probability 0.2, and the precipitation change will fall in the vertical shaded band with probability 0.125. Thus, under our assumption that temperature and precipitation are independent, there is a probability of 0.025 that large warming would be manifested in the N-LM latitudes by a climate change in the intersection of the two shaded bands, in which case the expected yield of U.S. corn would be about 100, or 2.6% higher than in the canonical climate-crop scenario.

The full implications of the uncertainty about large global warming are assessed by laying Table I-9 over the expected-yield matrix for U.S. corn (Table I-7) and summing probabilities in the usual way. The resultant frequency distribution of expected yields is shown in Figure I-9, which is analogous to Figure I-8. The latter figure is obtained by overlaying the large-warming BND matrix (Table I-8) on the annual-yield matrix (Table I-4); it shows the spectrum of *annual* yields due to the variability of annual crop weather, assuming the *expected* climate state of the Large Warming Scenario. Figure I-9, on the other hand, shows the spectrum of *expected* yields due to the uncertainty about the precise climate state that might confront U.S. corn in the Large Warming Scenario.

In Table VI-4 we elaborate on the analogy between Figures I-8 and I-9. We have substituted the expression "average yield" for "expected yield" so that we may speak of "the expected average yield" rather than "the expected value of the expected yield." Just as the uncertainty about annual crop weather results in an average yield (97.5) less than the yield for average weather in the Large Warming Scenario (100.6), so does the uncertainty about climate change result in an expected average yield (95.4) less than the average yield for the expected climate change (97.5). These differences stem from the convexity of the respective yield response surfaces which underly the two distributions: the yields on both surfaces drop faster than they rise from the point determined by the expected climate change. The convexity also accounts for the negative skewness of both distributions.

As indicated by the coefficients of variability in Table VI-4 and by the shapes of the subject distributions themselves, the distribution of average yields is narrower than the distribution of annual yields. Nevertheless, the cumulative probability table in Figure I-9 suggests there is one chance in four that the average yield of U.S. corn would be 90.1 or smaller, whereas the canonical climate-crop scenario for large global warming projects an average yield of 97.5. The same table also suggests there are about three chances in ten that the Large Warming Scenario would even be favorable for U.S. corn yields (the 70th percentile of average yields is 100.5).

6-8 THE IMPLICATIONS OF CLIMATIC UNCERTAINTY: OTHER SCENARIOS, OTHER CROPS

In this section we examine the implications of the uncertainty about zonal climate change for all the climate scenarios and all the key crops.

Table VI-4

U.S. CORN IN THE LARGE WARMING SCENARIO: A COMPARISON OF TWO YIELD DISTRIBUTIONS

			YIELD DISTRIBUTION	
			FIGURE I-8	FIGURE I-9
		TYPE OF NORMALIZED RELATIVE YIELDS	Annual Yields Y	Average Yields $\bar{Y}$
		CAUSE OF UNCERTAINTY (independent variables)	Annual Crop Weather ΔT, ΔP	Climate Change $\Delta\bar{T}$, $\Delta\bar{P}$
		UNDERLYING YIELD FUNCTION	Figure IV-3	Figure V-2
LARGE WARMING SCENARIO		DISTRIBUTION OF THE INDEPENDENT VARIABLES	BND in Table I-8	Joint probabilities in Table I-9
		EXPECTED VALUES OF THE INDEPENDENT VARIABLES	$E(\Delta T) = +1.0^\circ C$ $E(\Delta P) = +2.0\%$	$E(\Delta\bar{T}) = +1.0^\circ C$ $E(\Delta\bar{P}) = +2.0\%$
			Average Crop Weather for Expected Climate Change	Expected Climate Change
		YIELD CORRESPONDING TO THE EXPECTED VALUES OF THE INDEPENDENT VARIABLES	$Y = 100.6$*	$\bar{Y} = 97.5$
			Yield at Average Crop Weather	Average Yield for Expected Climate Change
	YIELD STATISTICS	EXPECTED VALUE	$E(Y) = 97.5$	$E(\bar{Y}) = 95.4$
			Average Yield for Expected Climate Change	Expected Average Yield for Large Warming
		COEFFICIENT OF VARIABILITY	0.120	0.074
		SKEWNESS	−0.91	−0.48

* This value was interpolated from the Master Yield Grids (Appendix D-1).

The spread of *global* temperature changes in each climate scenario clearly admits ranges of crop responses, but we believe that the ranges discussed below are factitiously inflated. The climate-response model mechanically reflects not just the collective uncertainty of the climate panelists but also the distortion of that uncertainty by our assumptions and methodology.

Completing the documentation of U.S. corn, we display the distributions of expected yields that are implied by the uncertainty about temperatures and precipitation in the northern lower middle latitudes (Figure VI-19). All the distributions are negatively skewed, a property that U.S. corn has in common with the other key crops. In the passage from large global cooling to large global warming (left to right in the first row and right to left in the second) there is a rather regular transition in the shapes of the distributions, even though the coefficients of variability are essentially the same except in the Large Warming Scenario. The expected values of the distributions decrease steadily from 100.0 in large cooling to 95.4 in large warming, while the modes shift from the 105–110 yield interval in the Large Cooling Scenario to the 100–105 yield interval in the other scenarios.

For what they may be worth, the worst-case implications of the combined uncertainty about temperature and precipitation changes are summarized in Table VI-5. The table contains the expected values and the coefficients of variability (CVs) of the *pro forma* distributions of expected yields held to be possible in virtue of the overstated uncertainty about the climate scenarios.

As one would expect from the earlier discussion of Figures I-8 and I-9, Table VI-5 has some features in common with the analogous Table III-6, which gives the same data for the distributions of *annual* yields projected in the canonical climate-crop scenarios. In both tables, for example, there is little pattern in the statistics for the two rice crops and Brazilian soybeans. These three subtropical crops aside, both tables exhibit the following pattern: in the progression from the Large Cooling Scenario to the Large Warming Scenario, the expected values of the yield distributions tend either to increase or decrease. There are seven crops whose maximum expected yields lie in the large-cooling columns of both tables, and whose maximum CVs fall in the large-warming columns. Otherwise, the two tables differ with regard to the CVs. In Table III-6, the CVs of most crops increase or decrease across the scenarios, so that the maximum CV is in one of the extreme climate scenarios. In Table VI-5, on the other hand, none of the sequences of CVs is monotonic. That the CVs behave differently in the two tables can be explained by the methodology. The regularity of the CVs in a given row of Table III-6 arises from moving essentially the same BND matrix on the matrix of an-

Table VI-5

UNCERTAINTY ABOUT EXPECTED YIELDS IN THE FIVE CLIMATE SCENARIOS

Crop and Country	Large Cooling		Moderate Cooling		Same		Moderate Warming		Large Warming	
	Prob=0.10		Prob=0.25		Prob=0.30		Prob=0.25		Prob=0.10	
	$E(\bar{Y})$	CV	$E(\bar{Y})$	CV	$E(\bar{Y})$	CV	$E(\bar{Y})$	CV	$E(\bar{Y})$	CV
CORN										
ARGENTINA	103.3	0.090	99.5	0.086	98.2	0.089	96.9	0.089	95.7	0.106
U.S.	100.0	0.064	99.0	0.060	97.4	0.064	96.9	0.064	95.4	0.074
RICE										
INDIA	97.8	0.082	97.6	0.083	98.4	0.068	98.0	0.068	98.2	0.076
PRC	97.9	0.051	97.9	0.052	98.4	0.043	98.3	0.044	98.1	0.049
SOYBEANS										
BRAZIL	97.5	0.086	96.6	0.090	97.2	0.076	96.3	0.077	95.5	0.086
U.S.	99.8	0.076	99.0	0.070	98.1	0.073	97.8	0.074	97.3	0.087
SPRING WHEAT										
CANADA	89.5	0.106	93.6	0.106	98.9	0.090	101.4	0.103	105.7	0.098
U.S.	97.7	0.086	97.6	0.089	98.2	0.075	98.4	0.086	98.7	0.080
USSR	91.7	0.124	94.2	0.126	98.5	0.102	100.7	0.116	104.7	0.107
WINTER WHEAT										
ARGENTINA	101.8	0.070	98.9	0.070	97.6	0.074	96.4	0.074	94.5	0.087
AUSTRALIA	104.0	0.105	99.6	0.096	98.0	0.099	96.5	0.099	94.5	0.117
INDIA	100.5	0.069	99.4	0.070	97.6	0.067	96.4	0.065	94.9	0.070
PRC	97.7	0.084	98.1	0.076	98.9	0.079	99.2	0.080	100.3	0.095
U.S.	101.2	0.085	99.5	0.077	98.3	0.080	97.9	0.080	97.5	0.091
USSR	92.1	0.096	94.7	0.097	98.8	0.078	100.8	0.088	104.3	0.080

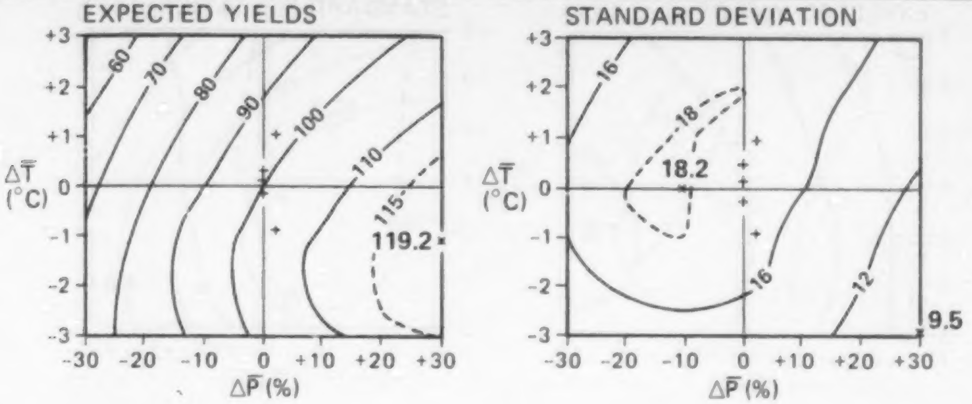
$E(\bar{Y})$ = Expected average yield CV = Coefficient of Variability nual yields. In Table VI-5, however, the CVs result from superimposing different matrices of joint probabilities on the matrix of expected yields.

Throughout this report we have called attention to the elements of uncertainty which permeate Task II. In particular, we have dwelt on the ranges of uncertainty about the zonal details of the climate scenarios. This uncertainty, if taken at face value, allows for an unrealistic range of yield responses in each scenario. In Appendix E-3 we suggest possible ways to reduce the climatic uncertainty. (Additional suggestions for improving the study are proffered in Appendix E-4.) We think that the uncertainty about zonal temperature changes is of minor consequence, but that the lack of consensus about precipitation changes could have biased the yield projections. Nevertheless, we proceeded with the climate impact assessment in the belief that the expected values of the precipitation changes were the best estimates available.

Figure VI-1

CORN: *Argentina*

Climate Response Surfaces (100 = Expected Yield in the Base Period)



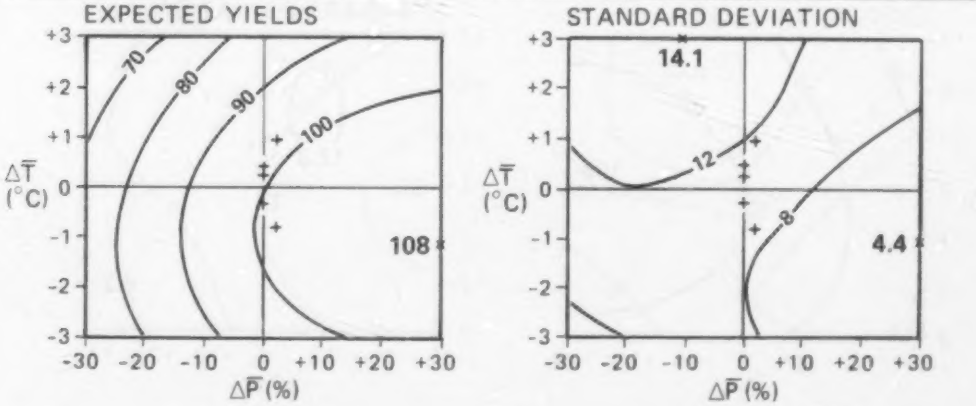
EXPECTED YIELDS

STANDARD DEVIATION

Figure VI-2

CORN: *U.S.*

Climate Response Surfaces (100 = Expected Yield in the Base Period)



EXPECTED YIELDS

STANDARD DEVIATION

Figure VI-3

RICE: *India*

Climate Response Surfaces (100 = Expected Yield in the Base Period)

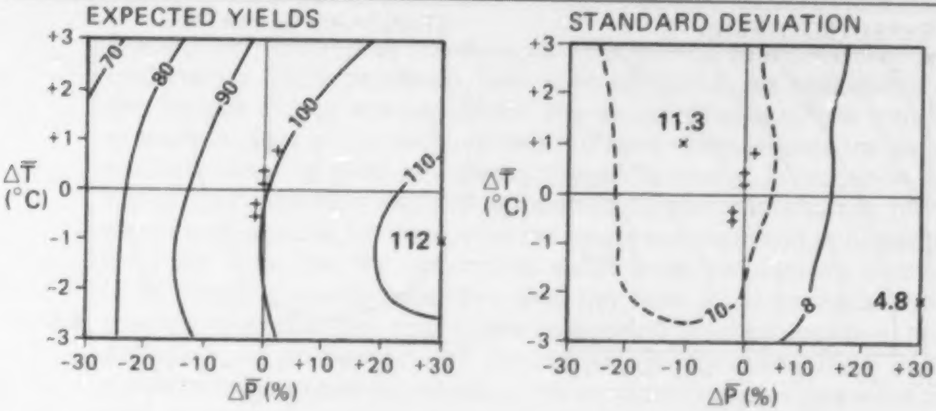


Figure VI-4

RICE: *PRC*

Climate Response Surfaces (100 = Expected Yield in the Base Period)

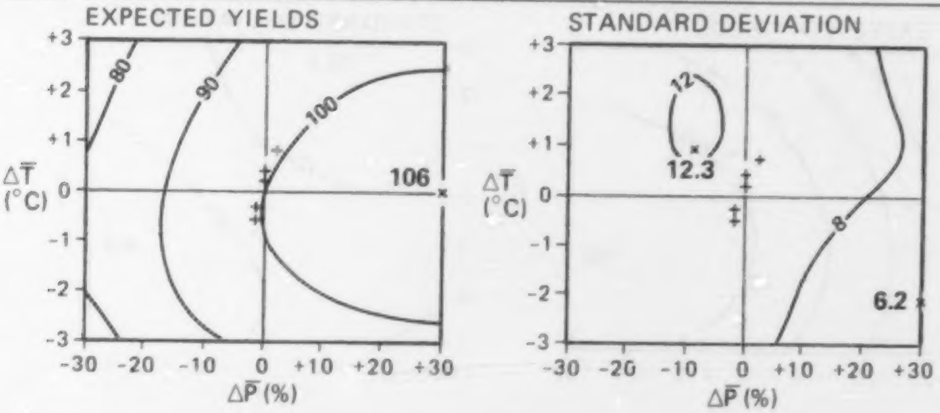


Figure VI-5

SOYBEANS: *Brazil*

Climate Response Surfaces (100 = Expected Yield in the Base Period)

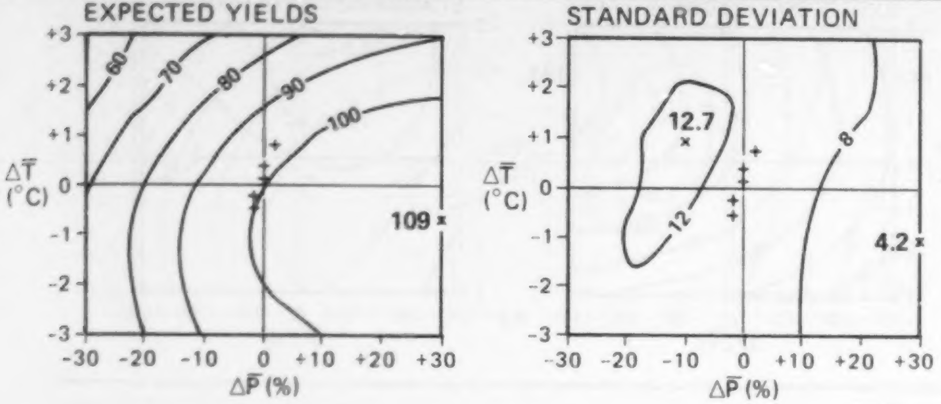


Figure VI-6

SOYBEANS: *U.S.*

Climate Response Surfaces (100 = Expected Yield in the Base Period)

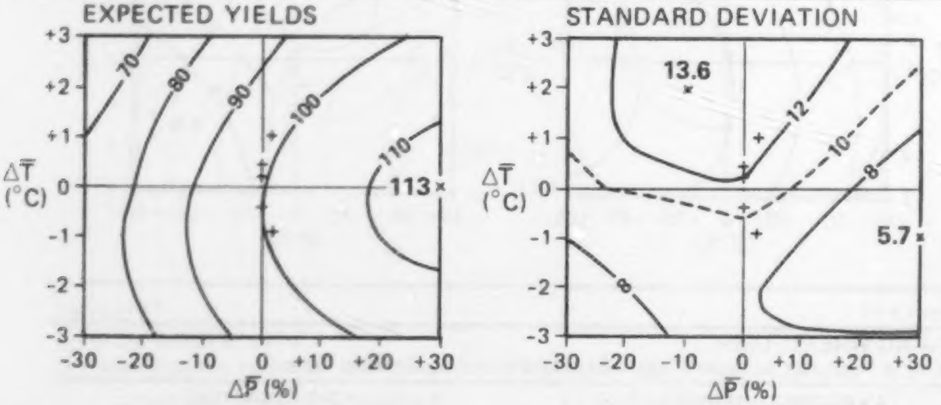


Figure VI-7

SPRING WHEAT: *Canada*
Climate Response Surfaces (100 = Expected Yield in the Base Period)

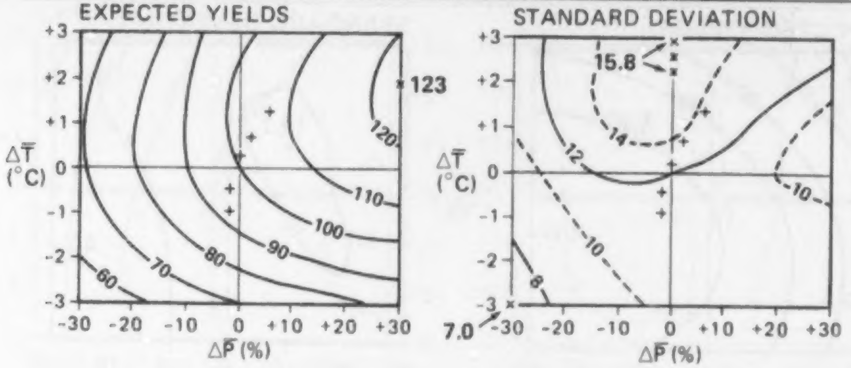


Figure VI-8

SPRING WHEAT: *U.S.*
Climate Response Surfaces (100 = Expected Yield in the Base Period)

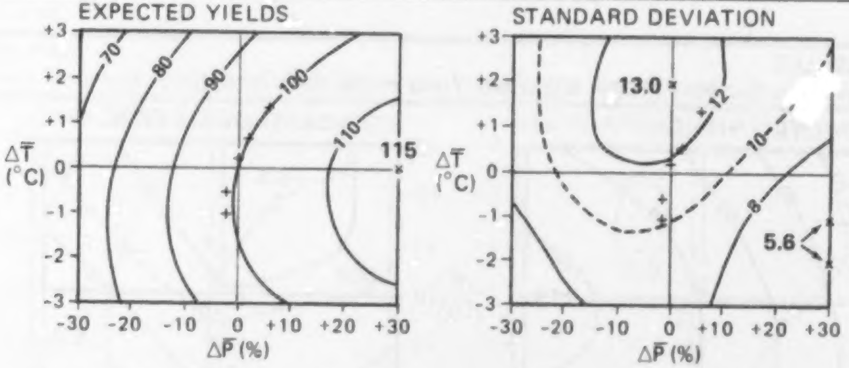


Figure VI-9

SPRING WHEAT: *USSR*
Climate Response Surfaces (100 = Expected Yield in the Base Period)

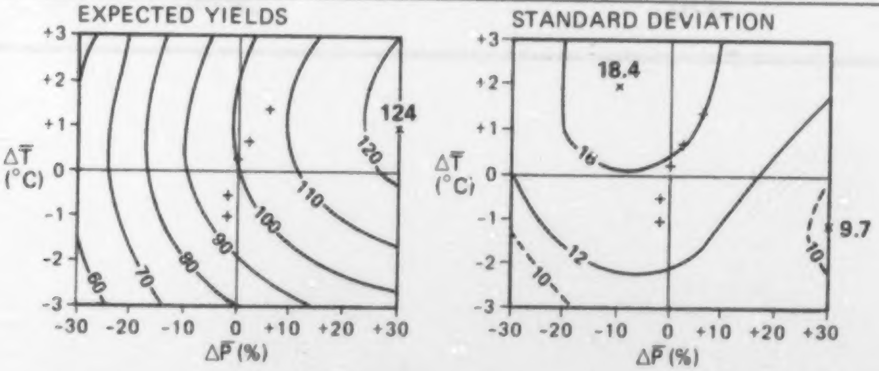


Figure VI-10

WINTER WHEAT: *Argentina*

Climate Response Surfaces (100 = Expected Yield in the Base Period)

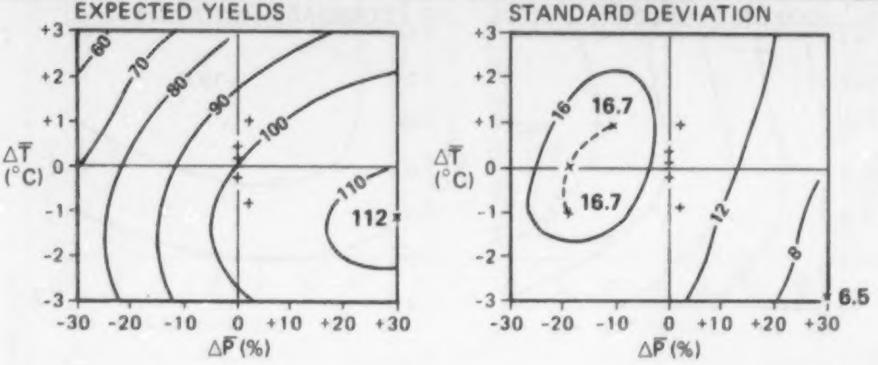


Figure VI-11

WINTER WHEAT: *Australia*

Climate Response Surfaces (100 = Expected Yield in the Base Period)

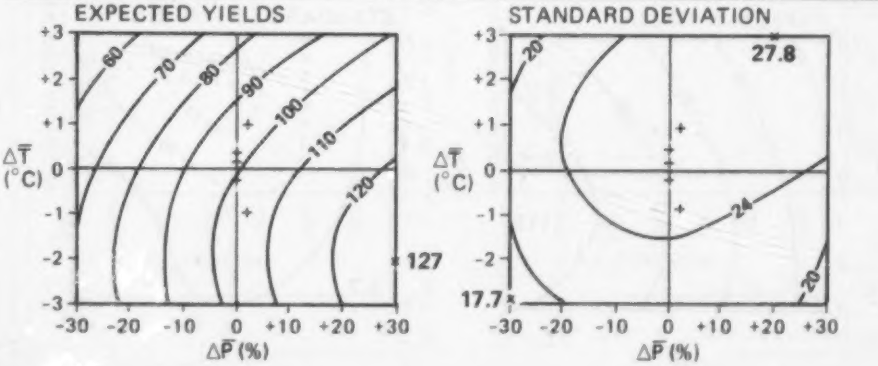


Figure VI-12

WINTER WHEAT: *India*

Climate Response Surfaces (100 = Expected Yield in the Base Period)

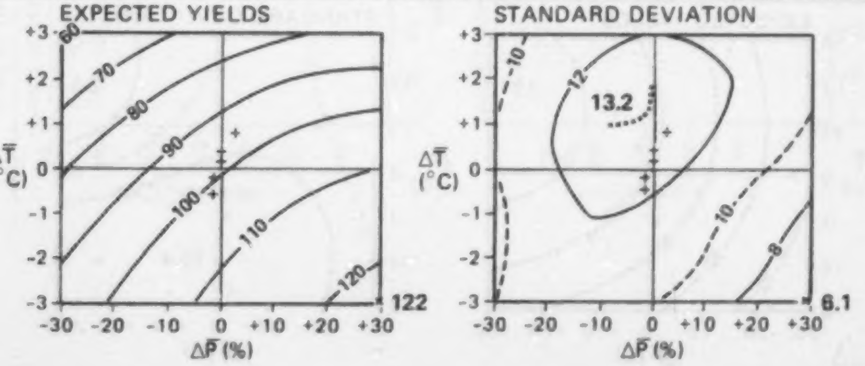


Figure VI-13

WINTER WHEAT: ***PRC***

Climate Response Surfaces (100 = Expected Yield in the Base Period)

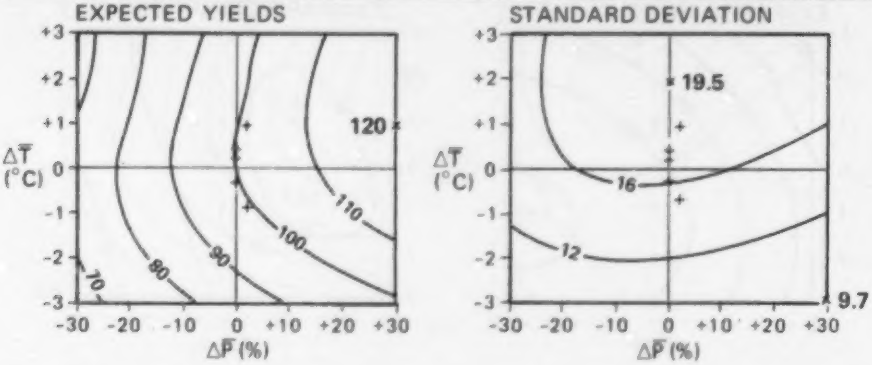


Figure VI-14

WINTER WHEAT: ***U.S.***

Climate Response Surfaces (100 = Expected Yield in the Base Period)

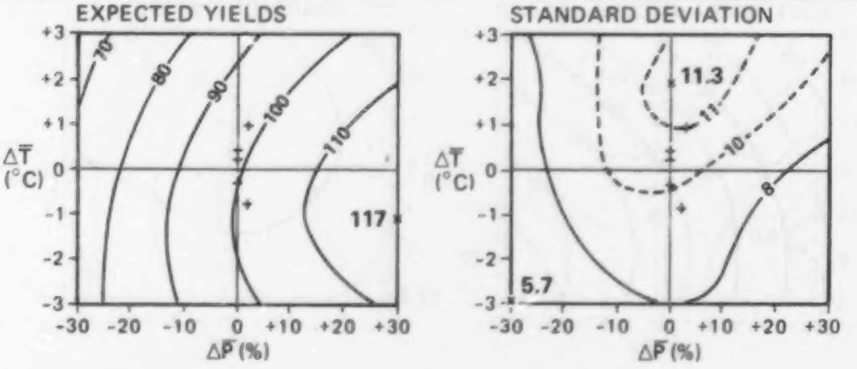


Figure VI-15

WINTER WHEAT: ***USSR***

Climate Response Surfaces (100 = Expected Yield in the Base Period)

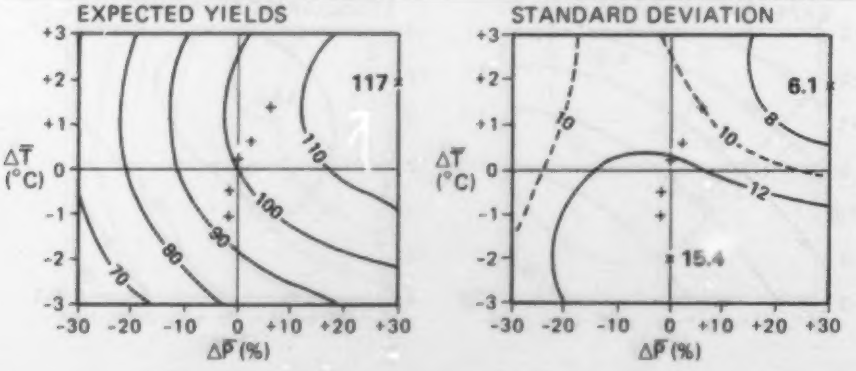
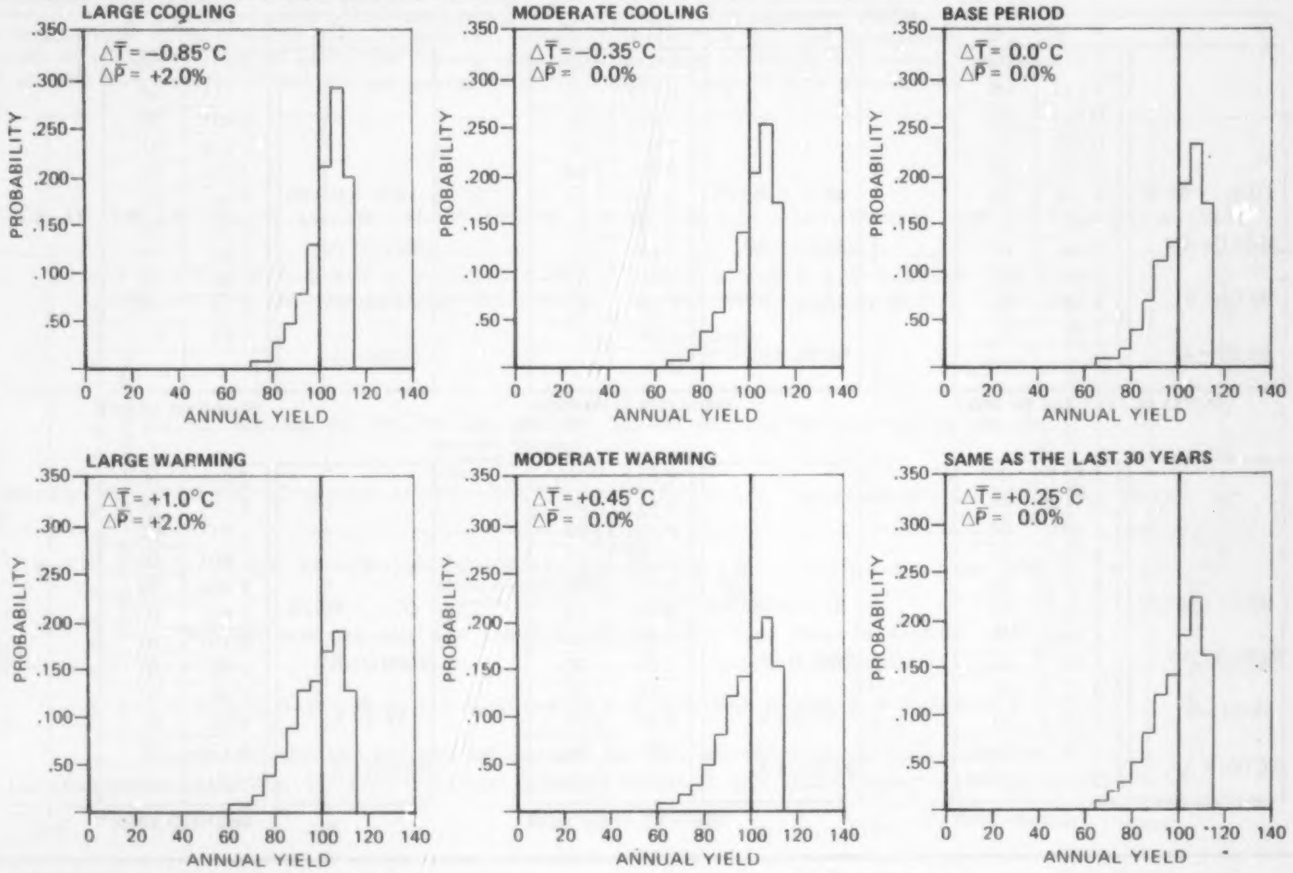


Figure VI-16

U.S. CORN: FREQUENCY DISTRIBUTIONS OF ANNUAL YIELDS FOR THE FIVE GLOBAL CLIMATE SCENARIOS AND THE BASE PERIOD (1976 TECHNOLOGY)



Each histogram of normalized relative yields is based on the expected climate change ($\Delta\overline{T}$, $\Delta\overline{P}$). (100 = Expected Yield in the Base Period)

Figure VI-16 (cont.)

CUMULATIVE PROBABILITIES (PROB) OF ANNUAL YIELDS AND RELATED STATISTICS:

LARGE COOLING

PROB	YIELD
0	51.3
10	90.6
20	96.3
30	99.4
40	101.8
50	104.7
60	106.4
70	108.2
80	110.0
90	111.6
100	113.2

$\bar{Y} = 102.33$

S = 8.74

CV = 0.0854

SKEW = -1.27

MODERATE COOLING

PROB	YIELD
0	48.0
10	86.9
20	92.7
30	97.1
40	100.5
50	102.6
60	105.4
70	107.5
80	109.4
90	111.5
100	113.2

$\bar{Y} = 100.74$

S = 9.87

CV = 0.0980

SKEW = -1.15

BASE PERIOD

PROB	YIELD
0	46.5
10	85.6
20	91.8
30	96.2
40	99.5
50	102.0
60	105.1
70	107.3
80	109.2
90	111.5
100	113.2

$\bar{Y} = 100.01$

S = 10.46

CV = 0.1046

SKEW = -1.09

LARGE WARMING

PROB	YIELD
0	42.5
10	81.3
20	88.0
30	92.3
40	96.3
50	99.5
60	102.7
70	105.7
80	108.3
90	111.1
100	113.2

$\bar{Y} = 97.48$

S = 11.70

CV = 0.1200

SKEW = -0.91

MODERATE WARMING

PROB	YIELD
0	44.1
10	83.3
20	89.5
30	93.7
40	97.6
50	100.8
60	103.8
70	106.4
80	108.7
90	111.4
100	113.2

$\bar{Y} = 98.60$

S = 11.21

CV = 0.1137

SKEW = -0.98

SAME AS THE LAST 30 YEARS

PROB	YIELD
0	45.2
10	83.9
20	90.5
30	94.9
40	98.5
50	101.4
60	104.6
70	107.0
80	109.0
90	111.4
100	113.2

$\bar{Y} = 99.29$

S = 10.88

CV = 0.1096

SKEW = -1.03

$\bar{Y}$ = Expected Value, S = Standard Deviation, CV = Coefficient of Variability, SKEW = Skewness

Figure VI-17

UNCERTAINTY ABOUT THE CLIMATE SCENARIOS IN THE NORTHERN LOWER MIDDLE LATITUDES

The Base Period (recent climate) is the reference point for long-term changes in temperature ($\Delta\overline{T}$) and precipitation ($\Delta\overline{P}$). The rectangles are envelopes of the climate changes which have nonzero probabilities according to the climate panelists' aggregated distributions of $\Delta\overline{T}$ and $\Delta\overline{P}$. The expected climate changes correspond to the expected values of these distributions.

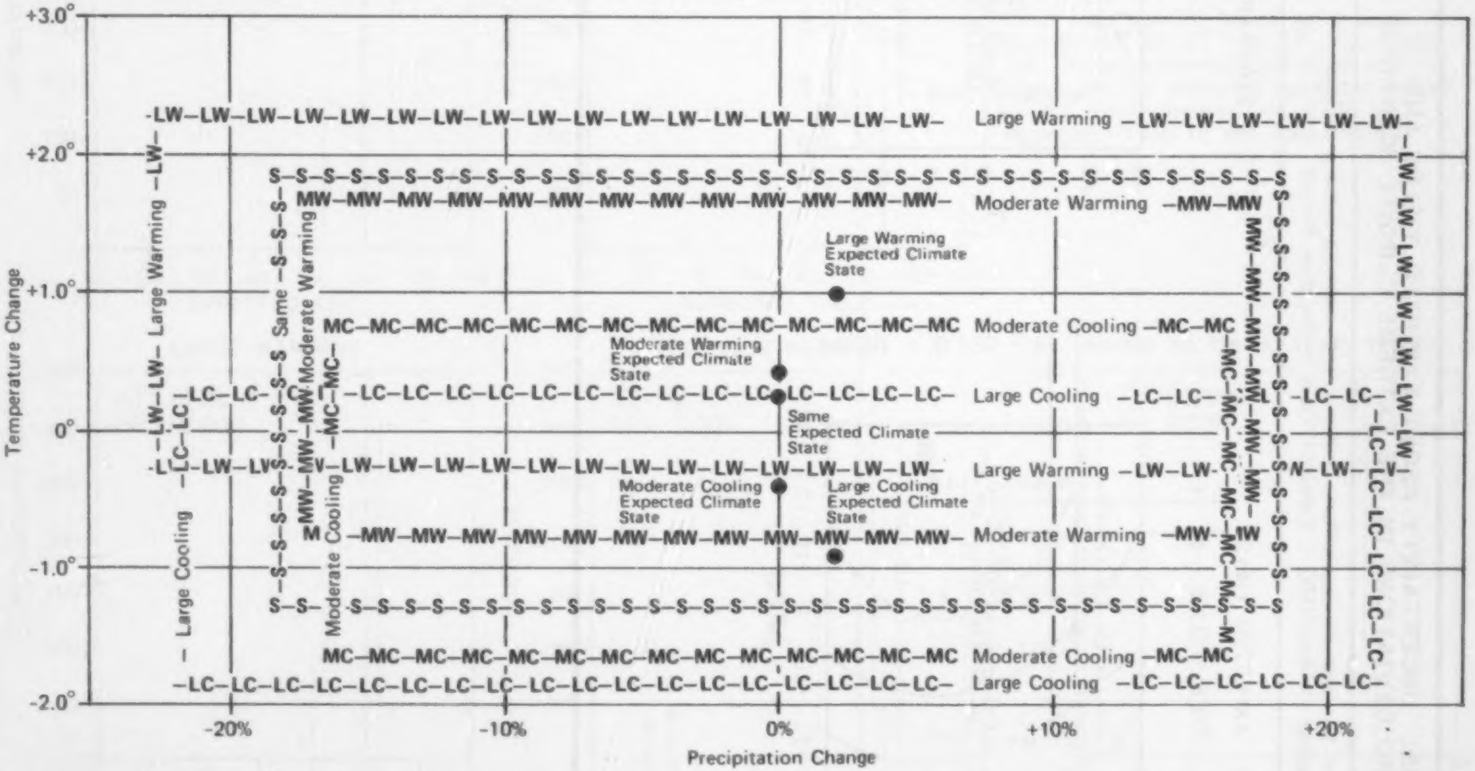
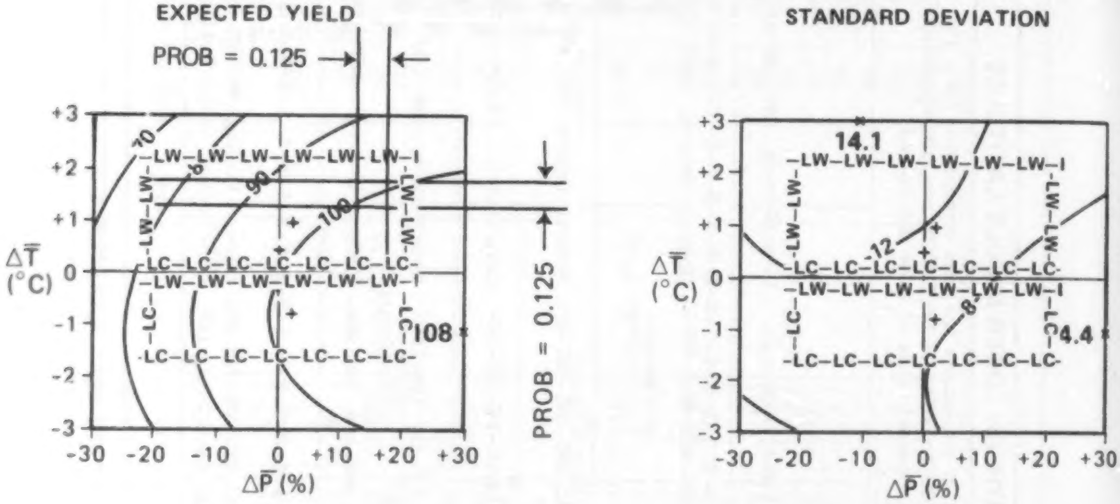


Figure VI-18

U.S. CORN: UNCERTAINTY ABOUT EXPECTED YIELDS AND STANDARD DEVIATIONS IN THE EXTREME CLIMATE SCENARIOS

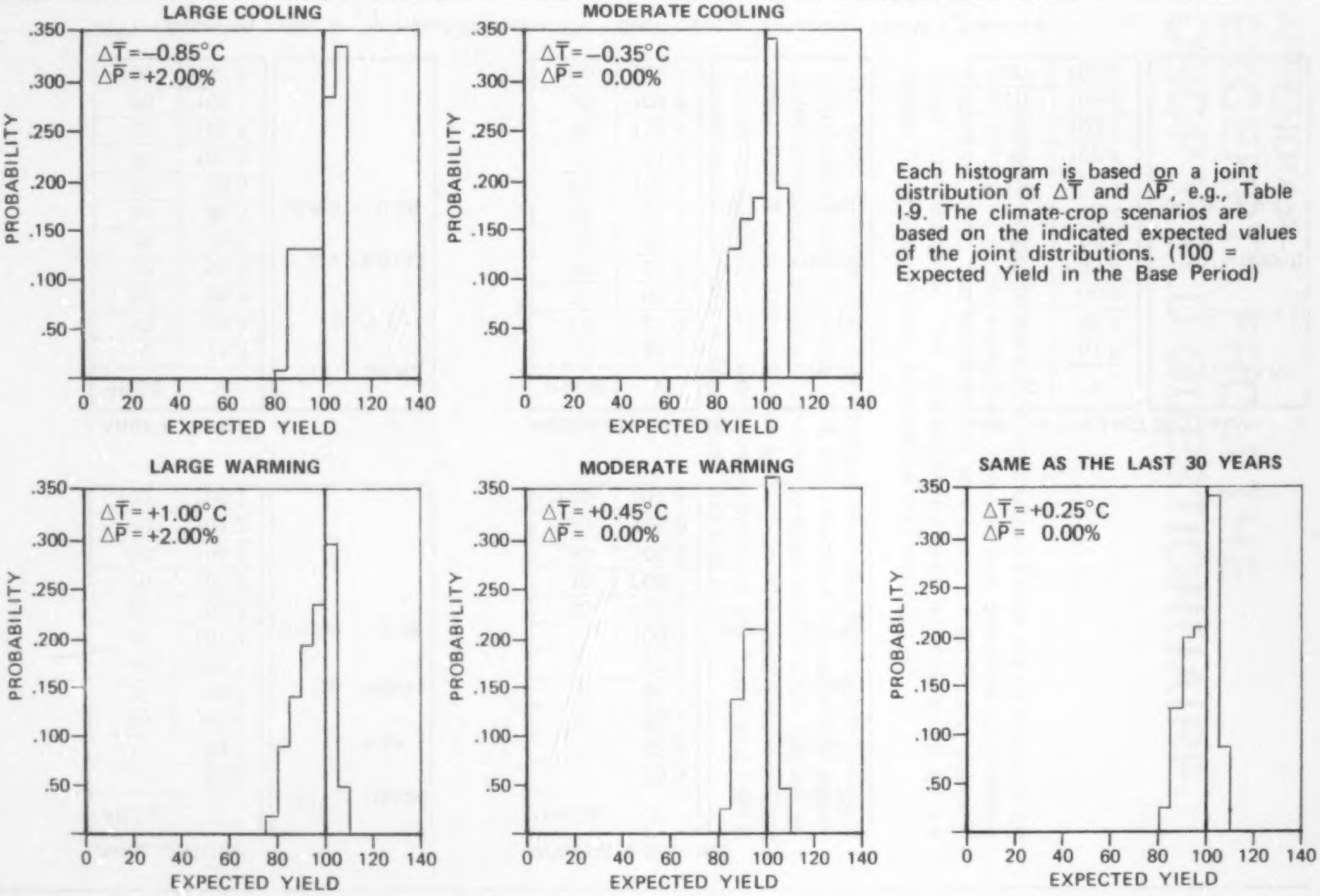
Envelopes of the large cooling scenario and the large warming scenario on the climate response surfaces. (100 = Expected Yield in the Base Period)



LW—Large Warming
LC—Large Cooling

Figure VI-19

U.S. CORN: FREQUENCY DISTRIBUTIONS OF EXPECTED YIELDS DUE TO UNCERTAINTY ABOUT THE PRECISE CLIMATE CHANGES IN THE FIVE GLOBAL CLIMATE SCENARIOS (1976 TECHNOLOGY)



Each histogram is based on a joint distribution of $\Delta\overline{T}$ and $\Delta\overline{P}$, e.g., Table I-9. The climate-crop scenarios are based on the indicated expected values of the joint distributions. (100 = Expected Yield in the Base Period)

Figure VI-19 (cont.)

CUMULATIVE PROBABILITIES (PROB) OF EXPECTED YIELDS ($\overline{Y}$) AND RELATED STATISTICS:

LARGE COOLING

PROB	$\overline{Y}$
0	83.0
10	89.1
20	93.4
30	96.9
40	100.1
50	101.4
60	103.4
70	105.3
80	106.3
90	107.2
100	108.2

$E(\overline{Y}) = 100.04$

S = 6.44

CV = 0.0644

SKEW = -0.58

MODERATE COOLING

PROB	$\overline{Y}$
0	85.8
10	88.9
20	93.1
30	96.1
40	97.2
50	100.3
60	102.4
70	103.1
80	105.0
90	105.9
100	107.2

$E(\overline{Y}) = 98.95$

S = 5.91

CV = 0.0597

SKEW = -0.46

LARGE WARMING

PROB	$\overline{Y}$
0	74.3
10	84.4
20	88.9
30	90.9
40	94.3
50	96.3
60	98.6
70	100.5
80	102.4
90	104.1
100	107.5

$E(\overline{Y}) = 95.42$

S = 7.10

CV = 0.0744

SKEW = -0.48

MODERATE WARMING

PROB	$\overline{Y}$
0	81.5
10	87.9
20	90.7
30	92.9
40	96.1
50	98.3
60	100.1
70	101.2
80	102.9
90	104.5
100	106.7

$E(\overline{Y}) = 96.92$

S = 6.21

CV = 0.0641

SKEW = -0.43

SAME AS THE LAST 30 YEARS

PROB	$\overline{Y}$
0	81.5
10	88.1
20	90.9
30	93.5
40	96.3
50	98.4
60	100.3
70	102.4
80	103.1
90	104.9
100	107.2

$E(\overline{Y}) = 97.40$

S = 6.24

CV = 0.0640

SKEW = -0.43

$E(\overline{Y})$ = Expected Value, S = Standard Deviation, CV = Coefficient of Variability, SKEW = Skewness

APPENDIX A-1

EXCERPTS FROM THE CROP-YIELD QUESTIONNAIRE

The general instructions to the Agriculture Panel are reproduced on the following pages along with the two-part question concerning Argentine corn. The same format was used for all fifteen country-crop combinations. The questionnaire was accompanied by an appendix of background information (not reproduced).

The yield histories that were presented in the Part I questions are incorporated into Appendix B-1, the record of the panelists' aggregated projections of technology trends from 1976 to 2000. The aggregated Part II estimates (yield as a function of annual crop weather) appear in Appendix D-1. Verbal responses to the Part I and Part II questions are compiled in Appendixes B-3 and D-2.

GENERAL INSTRUCTIONS

In this pamphlet we request your best judgments of probable changes in yields for selected crops in major producing areas of the world. In addition, you are asked to indicate your level of expertise in making your estimates. All individual replies will be held in strict confidence. The analysis of the aggregated responses will be furnished to all participants and will be included in a final report.

Appendix A* contains a limited amount of background information on the various countries, including descriptive materials and maps, that may be useful in making your estimates. We do not expect you to do new research; rather, we are asking for your perceptions of the evidence available to you. We would appreciate a rationale for your responses in any remarks you may wish to add.

For each of 15 country-crop combinations, two types of estimates are requested: the first dealing with the influence of technology on crop yields and the second with the responses of crops to temperature and precipitation changes.

Part I of each country-crop combination asks for projections of yields to the year 2000 assuming no change from present climate patterns but taking account of the likely rate of adoption of currently available or new technology.

Part II of each country-crop combination calls for filling out matrices to indicate probable relative crop responses to selected temperature and precipitation changes, assuming no change from the technology currently in use in the country.

We desire estimates of crop yield responses which:

- are spatially averaged over the crop area; and
- assume , for a single crop season, a "normal" temporal distribution of temperature and precipitation for each indicated change in these variables

Using information about the year-to-year climatological variance for each country-crop combination, we intend to calculate expected new mean yields after an assumed climate change by combining the Part II crop response matrix with bivariate normal frequency distributions of temperature and precipitation. The shapes of these distributions are determined by the variance and covariance of the two climate parameters. The variance and covariance, in turn, may be based either on historical data (to represent "present" climatic variability) or on assumptions about future year-to-year variability of temperature and precipitation. The crop yield matrices represent spatially averaged responses to annual weather. From these matrices we can calculate the time-averaged response to climate changes for various scenarios. The time averaging will include the effect of changing climate means and the effect of year-to-year climate variability. We will also be able to handle questions about the year-to-year variability of crop yields resulting from the year-to-year variability of temperature and precipitation.

On the following page is a sample response for Part II for a hypothetical crop and country. The figures given in the matrices are estimates of probable yield changes, given the indicated changes in temperature and precipitation, but assuming constant technology. Your estimates may be based on some specific "model," or alternatively, you may use your intuitive judgment of weather-crop yield interaction–based on your research or that of others–for that particular country-crop combination or for some other area where you feel the response would be roughly analogous.

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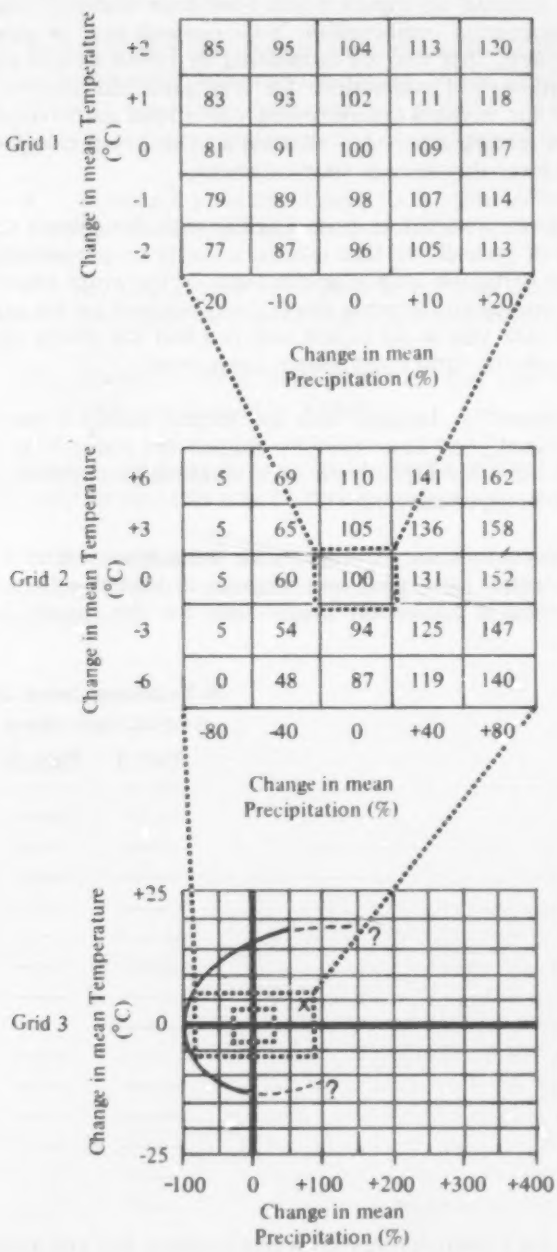
*This appendix is not included here.

SAMPLE

Country "X" Crop "Y"
PART II



Grid 1

Change in mean Temperature (°C)	-20	-10	0	+10	+20
+2	85	95	104	113	120
+1	83	93	102	111	118
0	81	91	100	109	117
-1	79	89	98	107	114
-2	77	87	96	105	113

Change in mean Precipitation (%)

Grid 2

Change in mean Temperature (°C)	-80	-40	0	+40	+80
+6	5	69	110	141	162
+3	5	65	105	136	158
0	5	60	100	131	152
-3	5	54	94	125	147
-6	0	48	87	119	140

Change in mean Precipitation (%)

Shown in Grids 1 and 2 on the left are judgment estimates of the probable change in yield (given as a percentage of average yields) of Crop "Y" in Country "X" that might be expected from the given changes in mean temperature and precipitation for the crop season.

Although the sample given here shows average yield (100 %) with zero change in mean temperature and precipitation, note that the yield resulting from average weather will not necessarily be–and frequently is not–the average yield.

Grid 3 outlines the approximate region within which it is estimated that some yield is possible. Theoretically, of course, this is a closed curve. We would like to have you define the entire region but we recognize that the lack of experimental data under conditions of very heavy rainfall may make it difficult or impossible for you to judge where zero yields occur under such conditions, i.e., the right-hand portion of the curve. Point "X" is an estimate of the weather conditions under which maximum yields are likely to occur- in this hypothetical case both temperature and precipitation are above normal.

CROP QUESTIONNAIRE

We recognize that you probably have more expertise for certain countries and crops than for others. Therefore, would you please indicate in the table below, for each of the 15 country-crop combinations, your numerical level of expertise, using the following self-rating definitions:

(4) EXPERT–You should consider yourself an expert if you have done research, whether in-country or not, on that particular country-crop combination. Your research may or may not have included development of specific "models," but you are considered by others to have a good understanding of the technology and weather-yield interactions for that particular crop in that environment. Typically, you know the US and non-US literature and you attend conferences and seminars relating to the subject, sometimes reading a paper or chairing a session. Other experts in this field may disagree with your views but invariably respect your judgment.

(3) QUITE FAMILIAR–You should rate yourself as quite familiar with the subject matter if, even though you have done little research yourself on that specific country-crop combination, you have done substantial research on that particular crop in another area of the world where you feel the yield responses would be roughly analogous. In other words, your research on the specific crop in another area of the world would rate you as an expert and you feel the results of that research are substantially applicable to the country-crop combination being rated.

(2) FAMILIAR–You should rate yourself as familiar with the subject matter if you have done little if any research on the crop yourself, but have carefully studied the research of other experts and on the basis of this evidence have developed your own opinions on expected yield responses for the country-crop combination being considered.

(1) UNFAMILIAR–You should rate yourself as unfamiliar with the subject matter if you have little or no familiarity with the crop, either from your own research or that of others, or if you feel that any knowledge you do possess is completely inapplicable for the country being considered.

Country-Crop	Self-ranking, based on 4-point scale above	
	Part I	Part II
Argentina corn	____	____
Argentina wheat	____	____
Australia wheat	____	____
Brazil soybeans	____	____
Canada wheat	____	____
India rice	____	____
India wheat	____	____
People's Republic of China rice	____	____
People's Republic of China winter wheat	____	____
US corn	____	____
US soybeans	____	____
US spring wheat	____	____
US winter wheat	____	____
USSR spring wheat	____	____
USSR winter wheat	____	____

If you are unable to provide estimates for a given country-crop combination, but you know of others who are "expert" or "quite familiar" regarding that combination, we would appreciate your indicating their names and affiliations in the space provided in the Part II instructions for that country and crop.

PART I – ARGENTINA CORN*

On the facing page is a table and a plot of yields for this country-crop combination covering the period 1950-1976.

Assuming that the climate remains essentially the same as during this period of record (i.e., essentially the same means and variances for the weather variables that affect the crop), but taking into account your best judgment of probable changes in technology for this country-crop combination, indicate your projection of the general trend in yields to the year 2000 by:

- drawing a yield trend path to the year 2000 such that you estimate only 1 chance in 10 that the actual yield trend could be even lower.
- drawing a yield trend path to the year 2000 such that you estimate an even chance that the actual yield trend could be either lower or higher.
- drawing a yield trend path such that you estimate only 1 chance in 10 that the actual yield trend could be higher.

Please begin your three projection paths at Point A, which is the 1972-1976 average yield. The three yield trend paths may be drawn continuously in whatever form you deem appropriate.

In the space below, please state your line of reasoning for the family of paths you have drawn, referencing, if you wish, articles you or other scientists have written that help form the basis for your judgments.

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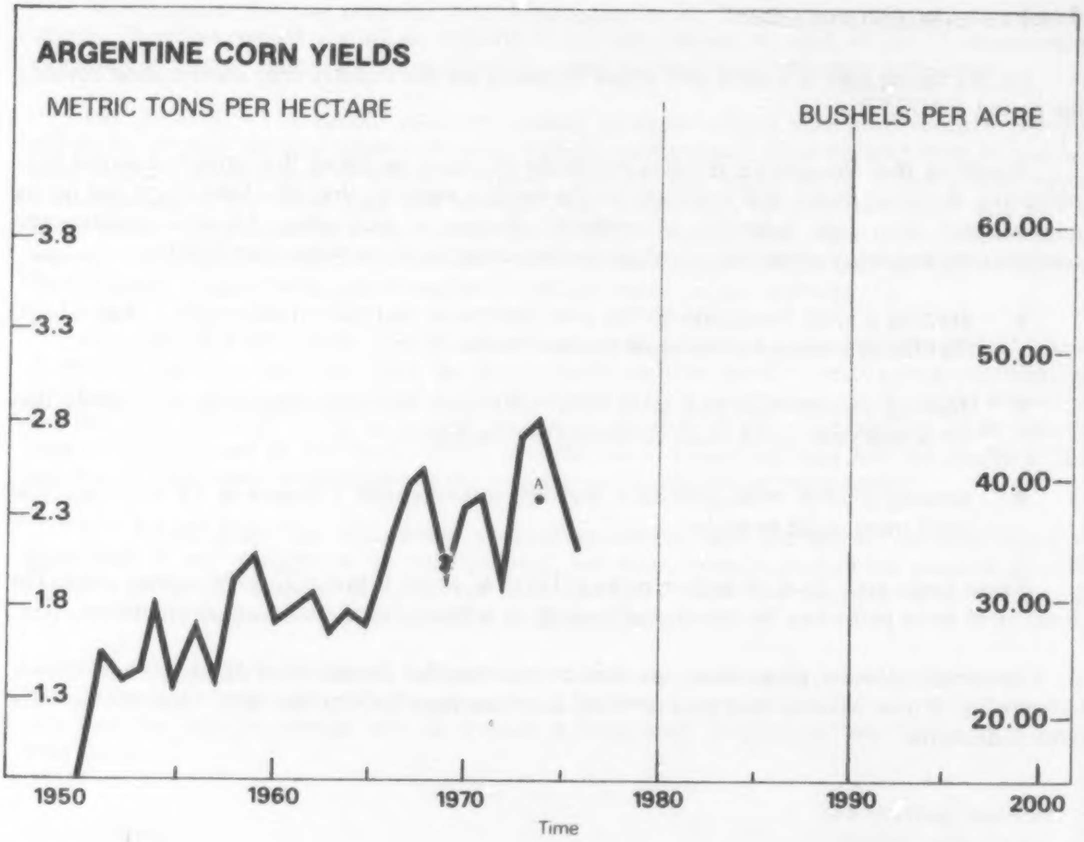
*NOTE: Part I was repeated for the other 14 country-crop combinations listed on the previous page. The Part I graphs and data presented for all the crops appear in Appendix B-1 along with the aggregated trend paths derived from the panelists' responses.



ARGENTINE CORN YIELDS

Point A = 1972-76 Average

Note Yield calculated on area harvested

Argentine Corn Yield Data

Year	Tons/ha.	Bus./acre	Year	Tons/ha.	Bus./acre	Year	Tons/ha.	Bus./acre
1950	.89	14.15	1960	1.70	27.11	1970	2.33	37.14
1951	1.56	24.83	1961	1.77	28.17	1971	2.44	38.93
1952	1.43	22.72	1962	1.89	30.18	1972	1.86	29.68
1953	1.51	24.02	1963	1.65	26.27	1973	2.72	43.37
1954	1.84	29.38	1964	1.80	28.70	1974	2.84	45.27
1955	1.37	21.77	1965	1.68	26.76	1975	2.51	39.98
1956	1.73	27.54	1966	2.15	34.26	1976	2.12	33.74
1957	1.38	21.96	1967	2.47	39.31	1980		
1958	1.96	31.29	1968	2.53	40.39	1990		
1959	2.09	33.29	1969	1.93	30.75	2000		

PART II – ARGENTINA CORN*

Following the format given in the grid samples in the General Instructions, indicate for each box in Grids 1 and 2 on the facing page, the change in yield that you would expect from the given changes in mean temperature and precipitation for the crop season. Please give your estimates as a percentage of the 1972-1976 average yield shown in the computer plot of Part I. Assume no change from current technology. For your information, spatially averaged reference levels for monthly mean temperature and precipitation are given in Appendix A.**

In Grid 3 on the facing page, outline the approximate region within which you feel some yield is possible, and mark the point of maximum yield with an "x."

Space is provided below for any explanatory or qualifying remarks you may wish to make concerning the estimates you enter in the grid matrices.

In the space below would you please identify (including institutional affiliation) two or three other scientists, whether among the listed panelists or not, whom you would rate as "expert" or "quite familiar" for this particular country-crop combination.

EXPERT (4) **QUITE FAMILIAR (3)**

---

*Part II was repeated for the other 14 country-crop combinations. Aggregations of the responses to Grids 1 and 2 for each combination appear in Appendix D-1. It was not deemed necessary to process the Grid 3 data.

**This appendix is not included here.

APPENDIX A–2

WEATHER/CLIMATE VARIABLES AND THE BIVARIATE NORMAL DISTRIBUTIONS

INTRODUCTION

The bivariate normal distributions for the Base Period were derived from records of temperature and precipitation as measured on absolute scales. In Task I and Task II, however, we chose to treat temperature and precipitation on an incremental or differential basis: annual crop weather is defined in terms of ΔT and ΔP (see Section 1–5), and climate change is defined in terms of $\Delta\overline{T}$ and $\Delta\overline{P}$ (see Section 1–9). The temperature variables ΔT and $\Delta\overline{T}$ are expressed in degrees Celsius, but the precipitation variables ΔP and $\Delta\overline{P}$, expressed as percentages, are relative measures without dimension. In this appendix we examine the absolute crop-weather variables that correspond to the differential variables.

Specifically, we show that our incremental notation is consistent with conventional usage of the delta and overbar symbols. To minimize the notation in the text and distance ourselves from absolute variables, we verbally defined the composite symbols ΔP, $\Delta\overline{T}$, etc., without explicitly bestowing any separate meaning on "Δ", "–" or the letters "P" and "T". Now it will be seen, for example, that $\Delta\overline{T}$ is indeed the result of applying the difference operator to the average (or expected) value of a variable T.

We also demonstrate functional relationships among the bivariate normal distributions of the several variables, considering both the Base Period and an arbitrary climate state.

CROP-WEATHER VARIABLES FOR THE BASE PERIOD

For this discussion we let T be an annual occurrence of mean *absolute* heading-period temperature with Base-Period average $\overline{T}_o$, and we let Q be an annual occurrence of mean *absolute* crop-year precipitation with Base-Period average $\overline{Q}_o$.

We then define a *relative* crop-year precipitation P by

(1) $$P = (100/\overline{Q}_o)Q.$$

The relative variable P therefore expresses crop-year precipitation as a percentage of the Base-Period average $\overline{Q}_o$. Moreover, $\overline{P}_o$, the average of P in the Base-Period, is equal to 100.

In this notation, the verbal definitions of ΔT and ΔP are equivalent to

$$\Delta T = T - \overline{T}_o,$$

and

$$\Delta P = (100/\overline{Q}_o)(Q - \overline{Q}_o) = P - \overline{P}_o.$$

Hence, one can interpret "Δ" as a difference operator: operating on T and P, Δ subtracts the respective Base-Period averages $\overline{T}_o$ and $\overline{P}_o$.

BIVARIATE NORMAL DISTRIBUTIONS FOR THE BASE PERIOD

If the joint distribution of T and Q in the Base Period were a bivariate normal distribution, it would take the standard form

(2) $$\mathrm{bnd}(T,Q) = \frac{1}{2\pi\sqrt{1-r^2}} \exp\left[-\frac{1}{2(1-r^2)} (Z_1^2 + Z_2^2 - 2rZ_1Z_2) \right],$$

where

$$Z_1 = (T - \overline{T}_o)/s_o(T), \; Z_2 = (Q - \overline{Q}_o)/s_o(Q).$$

The parameters which "shape" the function bnd(T,Q) are:

$s_o(T)$ = the standard deviation of T in the Base Period,
$s_o(Q)$ = the standard deviation of Q in the Base Period,
$r(T,Q)$ = the correlation coefficient for T and Q in the Base Period.

Now s_T, by which we have denoted the standard deviation of ΔT in the Base Period, is equal to $s_o(T)$.[1] Hence Z_1 is expressible in terms of the differential variable T:

$$Z_1 = \Delta T / s_T.$$

Similarly, s_P, the standard deviation of ΔP in the Base Period, is equal to $s_o(P)$, the corresponding standard deviation of P. It then follows from definition (1) that

$$s_P = s_o(P) = (100/\overline{Q}_o)s_o(Q).$$

---

[1] Here and elsewhere in this appendix we make repeated use of the following property of the standard deviation: if $y = ax + b$, then $s_y = as_x$.

Using this relation and definition (1) again, one finds that

$$Z_2 = \Delta P/s_p.$$

Since ΔT and ΔP are obtained from T and Q by linear transformations, the correlation coefficient r(T,Q) is equal to r, the correlation coefficient for ΔT and ΔP in the Base Period. Recalling from Section I-6 the expression for BND(ΔT,ΔP), the Base-Period bivariate normal distribution of ΔT and ΔP, and comparing that expression with the differential forms of Z_1 and Z_2, we get the following functional relationship:

$$\text{bnd}(T,Q) = \text{BND}(\Delta T,\Delta P). \tag{3}$$

But the derivation of equation (3) is reversible, so one could start with the expression for BND(ΔT,ΔP) and show that the distribution of T and Q is given by the right-hand side of equation (2). Thus, if the distribution of T and Q is bivariate normal, then so is the distribution of ΔT and ΔP, conversely.

CROP-WEATHER VARIABLES FOR AN ASSUMED CLIMATE CHANGE

Consider an arbitrary, but fixed, climate change ($\Delta\overline{T}$, $\Delta\overline{P}$). The variables T, Q, P have the same meaning as above, but we denote their respective long-term averages and standard deviations in the assumed climate state by $\overline{T}$, $\overline{Q}$, $\overline{P}$ and s(T), s(Q), s(P).

In symbols, our verbal definition of the climate change ($\Delta\overline{T}$,$\Delta\overline{P}$) is

$$\Delta\overline{T} = E(\Delta T),\ \Delta\overline{P} = E(\Delta P),$$

where E(   ) denotes expected value. But

$$E(\Delta T) = E(T-\overline{T}_o) = E(T)-\overline{T}_o = \overline{T}-\overline{T}_o,$$

and $E(\Delta P) = \overline{P}-\overline{P}_o$, whence

$$\Delta\overline{T} = \overline{T}-\overline{T}_o,\ \Delta\overline{P} = \overline{P}-\overline{P}_o.$$

Once again, "Δ" may be viewed as a difference operator that subtracts $\overline{T}_o$ or $\overline{P}_o$, the long-term Base-Period averages. Furthermore, the last equations confirm an assertion we made in Section 1-9:

$\Delta\overline{T}$= change in the long-term average of annual mean *absolute* heading-period temperature referred to the Base Period, and

$\Delta\overline{P}$= percentage change in the long-term average of the mean *absolute* crop-year precipitation referred to the Base Period.

BIVARIATE NORMAL DISTRIBUTIONS FOR AN ASSUMED CLIMATE CHANGE

In Section 1-10 we assumed that after a climate change the pattern of annual crop-weather fluctuations would be essentially the same as in the Base Period. We now consider the implications of the assumption for the distributions of the temperature and precipitation variables.

One part of the assumption is the persistence of the correlation between ΔT and ΔP (hence between T and Q). Thus, we can use r to stand for all temperature-precipitation correlation coefficients in all climate states. Similarly, because of the assumed invariance of the standard deviation of temperature, the symbol s_T suffices for the standard deviations of both T and ΔT in all climate states. The standard deviation of precipitation is assumed to change proportionately with the long-term average of crop-year precipitation. That is,

$$s(Q)/\overline{Q} = s_o(Q)/\overline{Q}_o.$$

From this and equation (1) it follows that

$$s(P)/\overline{P} = s_o(P)/\overline{P}_o = s_p/\overline{P}_o. \tag{4}$$

If we assume that T and Q have a bivariate normal distribution $\overline{\mathrm{bnd}}(T,Q)$ after the climate change $(\Delta\overline{T},\Delta P)$, then this function will have the same form as the right-hand side of (2), but with Z_1 and Z_2 replaced by

$$Z_1 = (T-\overline{T})/s(T),\ \overline{Z}_2 = (Q-\overline{Q})/s(Q).$$

Now, the numerator of $\overline{Z}_1$ can be written as

$$(T-\overline{T}_o) - (\overline{T}-\overline{T}_o) = \Delta T - \Delta\overline{T},$$

and the denominator is equal to s_T. Hence in terms of temperature increments,

$$\overline{Z}_1 = (\Delta T - \Delta\overline{T})/s_T. \tag{5}$$

Equation (1) and its consequence $s(P) = (100/\overline{Q}_o)s(Q)$ imply that

$$\overline{Z}_2 = (P-\overline{P})/s(P) = (\Delta P - \Delta\overline{P})/s(P).$$

From (4), we have

$$s(P) = s_p\overline{P}/\overline{P}_o = s_p\overline{P}/100.$$

Using this and the relation $\overline{P} = \overline{P}_o + \Delta\overline{P} = 100 + \Delta\overline{P}$, we get

$$(6) \qquad \bar{Z}_2 = 100(\Delta P - \overline{\Delta P})/(100 + \overline{\Delta P})s_p$$

as an expression for $\bar{Z}_2$ in terms of relative precipitation increments.

Comparing (5) and (6) with Z_T and Z_P in the expression for BND($\Delta T, \Delta P$), the Base-Period bivariate normal distribution, one can write the following generalization of equation (3):

$$(8) \qquad \overline{bnd}(T,Q) = BND([\Delta T - \overline{\Delta T}], k[\Delta P - \overline{\Delta P}]),$$

where

$$k = 100/(100 + \Delta P).$$

Again, the argument can be reversed. One notes that the full expression for the right-hand side of (8) reiterates the variability assumption: in the new climate state the annual crop-weather departures $T - \bar{T}$ and $P - \bar{P}$ (the bracketed variables) are distributed like ΔT and ΔP in the Base Period, except that s_p is multiplied by

$$\bar{Q}/\bar{Q}_o = \bar{P}/\bar{P}_o = 1/k.$$

Then, retracing steps, one can show that T and Q have a bivariate normal distribution of the form that was assumed at the beginning.

Equation (8) symbolizes what we mean by "shifting" a "modified" Base-Period BND matrix on the annual-yield matrix in order to calculate the frequency distribution of annual yields for an assumed climate change ($\overline{\Delta T}, \overline{\Delta P}$). The arguments $\Delta T - \overline{\Delta T}$ and $\Delta P - \overline{\Delta P}$ reflect the "shift," i.e., the translation of the BND matrix so that its center lies over that element of the yield matrix which corresponds to the assumed climate change. The scaling factor $100/(100 + \overline{\Delta P})$ reflects a "modification" of the precipitation dimension of the Base-Period BND matrix, a small price to pay for the dispensation of being able to work entirely with increments of the weather/climate variables rather than absolute values. Moreover, equation (8) shows that, given our assumption, one function suffices to describe the variability of crop weather in all climate states.

APPENDIX B–1

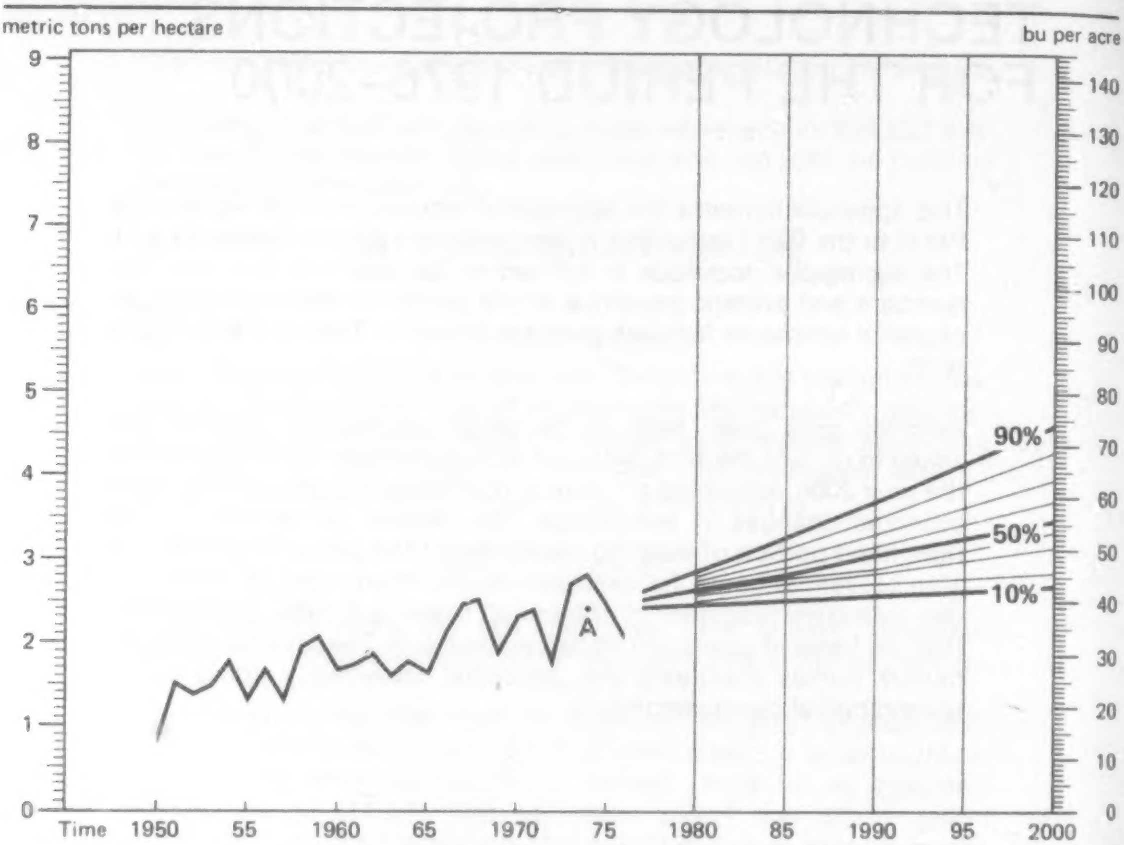
TECHNOLOGY PROJECTIONS FOR THE PERIOD 1976–2000

This appendix contains the aggregated responses of the Agriculture Panel to the Part I questions in the crop-yield survey (Appendix A-1). The aggregation technique is outlined in Sections 1–3 and 1–4. The numbers and average expertise of the panelists who submitted acceptable estimates for each crop are shown in Table II-1 and Figure IV-11.

Panelists were given plots of the yields reported for 1950–76 and asked to project the 10th, 50th and 90th percentiles of yield trends to the year 2000, assuming no change in climate but taking account of potential changes in technology. The labeled percentiles on the right-hand portion of each figure represent the group response. The 10th percentile curve, for example, can be interpreted as follows: in the collective judgment of the panel, there is a 10% "probability" that the trend of yields will lie below the curve. The spread of the percentile curves manifests the panelists' uncertainty about future technological developments.

Figure B-1.1

ARGENTINE CORN YIELDS



Point A = 1972-76 Average = 38.4 bu/a = 2.41 tons/ha

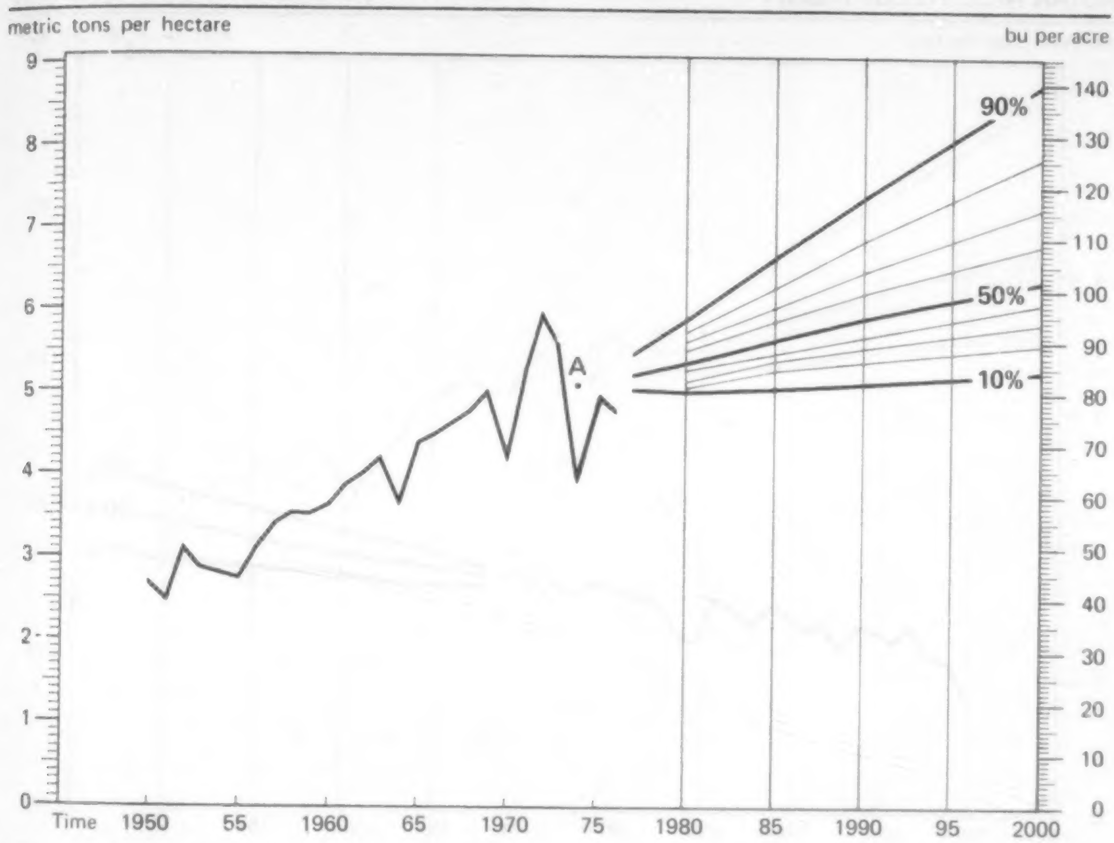
Note: Yield calculated on area harvested

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
	1950	.89	14.15	**1960**	1.70	27.11	**1970**	2.33	37.14
ARGENTINE CORN YIELD	1951	1.56	24.83	1961	1.77	28.17	1971	2.44	38.93
	1952	1.43	22.72	1962	1.89	30.18	1972	1.86	29.68
	1953	1.51	24.02	1963	1.65	26.27	1973	2.72	43.37
	1954	1.84	29.38	1964	1.80	28.70	1974	2.84	45.27
	1955	1.37	21.77	**1965**	1.68	26.76	**1975**	2.51	39.98
	1956	1.73	27.54	1966	2.15	34.26	1976	2.12	33.74
	1957	1.38	21.96	1967	2.47	39.31	*1980	2.69	42.84
	1958	1.96	31.29	1968	2.53	40.39	*1990	3.14	50.09
	1959	2.09	33.29	1969	1.93	30.75	*2000	3.64	57.92

*Mean of projected yields

Figure B-1.2

U.S. CORN YIELDS, SELECTED STATES [1]



Point A= 1972-76 Average = 81.4 bu/a = 5.11 tons/ha

Note: Yield calculated on area harvested

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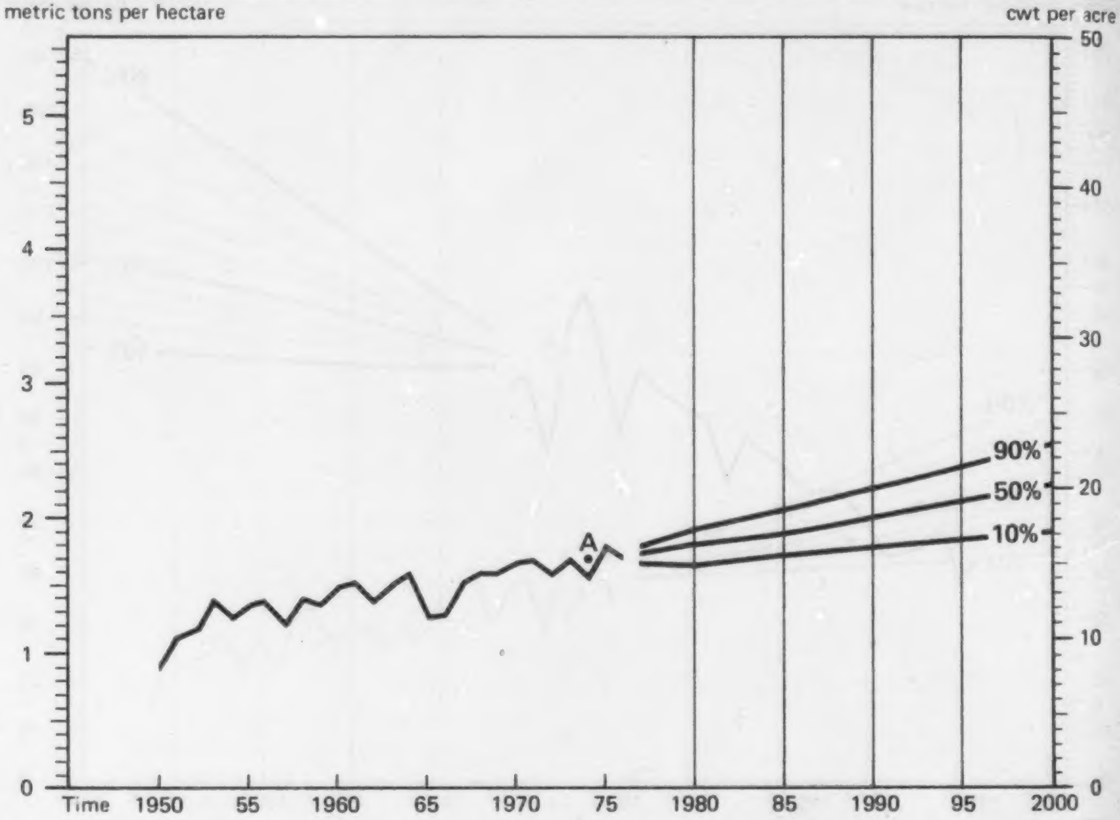
[1] Nine states - Ohio, Indiana, Illinois, Minnesota, Iowa, Missouri, Nebraska, South Dakota, and Wisconsin - account for about 80 percent of corn production.

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
U.S. CORN YIELDS	**1950**	2.74	43.62	**1960**	3.67	58.32	**1970**	4.32	68.72
	1951	2.55	40.48	1961	3.92	62.35	1971	5.34	84.98
	1952	3.17	50.44	1962	4.04	64.22	1972	6.03	95.92
	1953	2.91	46.29	1963	4.23	67.21	1973	5.64	89.72
	1954	2.84	45.13	1964	3.74	59.44	1974	4.09	64.97
	1955	2.77	44.17	**1965**	4.43	70.42	**1975**	4.96	79.13
	1956	3.17	50.40	1966	4.55	72.29	1976	4.85	77.38
	1957	3.42	54.38	1967	4.67	74.32	* 1980	5.47	87.08
	1958	3.58	56.89	1968	4.82	76.71	* 1990	6.13	97.68
	1959	3.54	56.32	1969	5.06	80.41	* 2000	6.74	107.32

* Mean of projected yields

Figure B-1.3

INDIAN RICE YIELDS (Paddy)



Point A = 1972-76 Average = 15.2 cwt/a

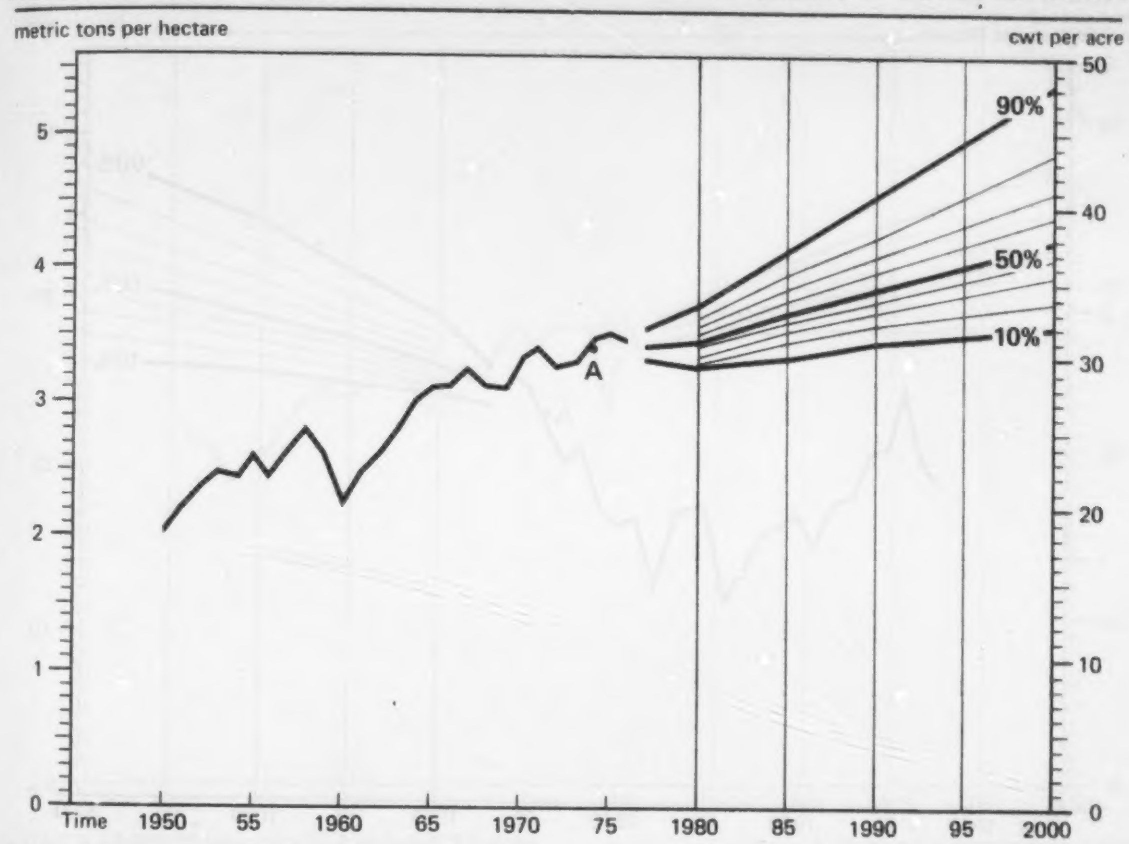
Note: Yield calculated on seeded area

	Year	tons/ha	cwt/a	Year	tons/ha	cwt/a	Year	tons/ha	cwt/a
INDIAN RICE YIELDS (Paddy)	**1950**	1.08	09.62	**1960**	1.52	13.60	**1970**	1.69	15.05
	1951	1.14	10.18	1961	1.55	13.83	1971	1.71	15.28
	1952	1.22	10.89	1962	1.40	12.52	1972	1.61	14.34
	1953	1.43	12.78	1963	1.55	13.84	1973	1.73	15.43
	1954	1.30	11.59	1964	1.62	14.44	1974	1.60	14.23
	1955	1.37	12.21	**1965**	1.29	11.55	**1975**	1.83	16.37
	1956	1.41	12.57	1966	1.30	11.57	1976	1.76	15.69
	1957	1.24	11.03	1967	1.55	13.83	*1980	1.83	16.32
	1958	1.45	12.96	1968	1.62	14.41	*1990	2.05	18.28
	1959	1.41	12.58	1969	1.61	14.38	*2000	2.28	20.30

*Mean of projected yields

Figure B-1.4

PRC RICE YIELDS (Paddy)



Point A= 1972-76 Average = 30.7 cwt/a = 3.4 tons/ha

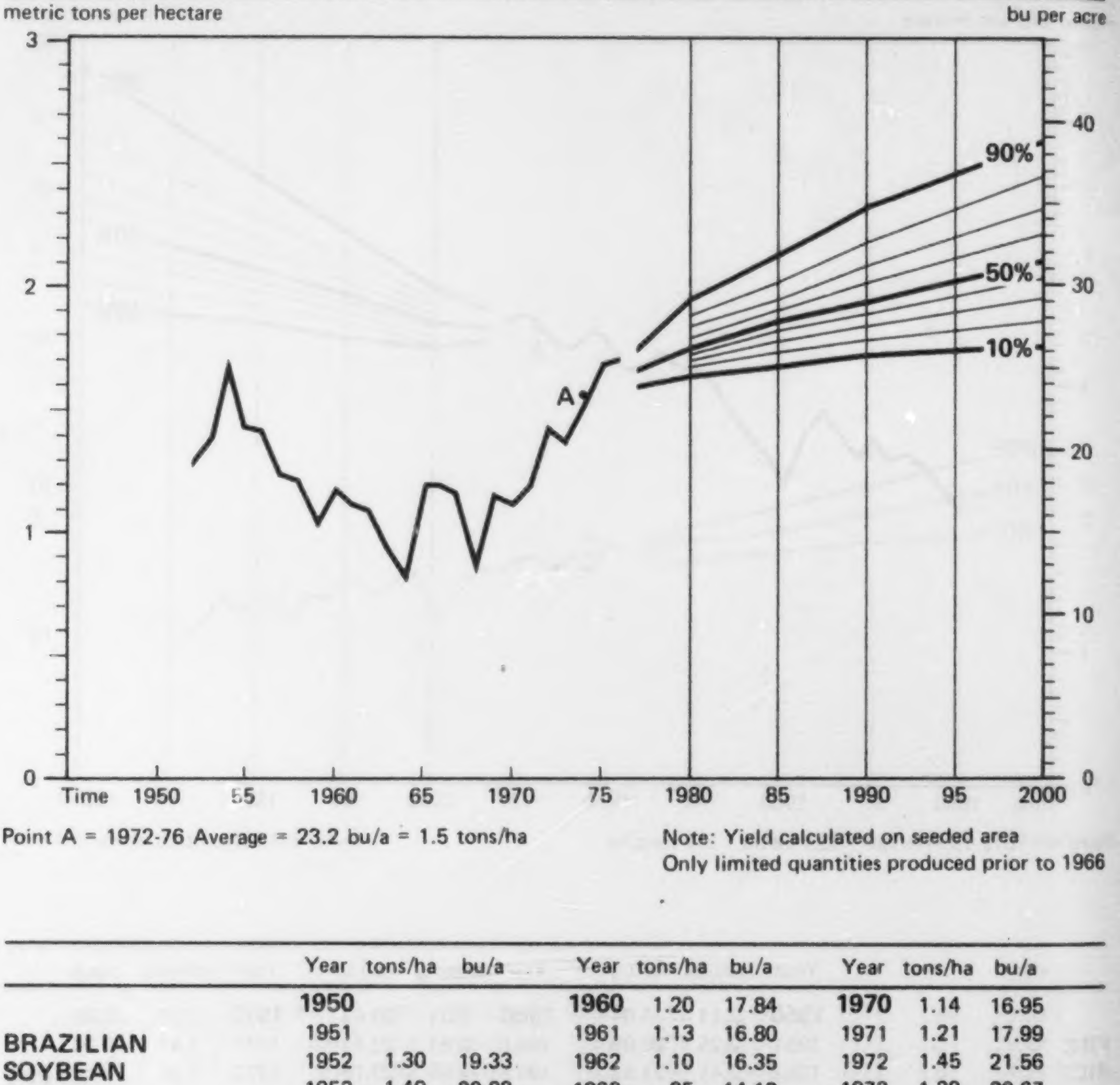
Note: Yield calculated on seeded area

	Year	tons/ha	cwt/a	Year	tons/ha	cwt/a	Year	tons/ha	cwt/a
PRC RICE YIELD	**1950**	2.11	18.84	**1960**	2.31	20.63	**1970**	3.37	30.09
	1951	2.25	20.09	1961	2.51	22.41	1971	3.47	30.98
	1952	2.41	21.52	1962	2.66	23.75	1972	3.32	29.64
	1953	2.52	22.50	1963	2.84	25.36	1973	3.35	29.91
	1954	2.47	22.05	1964	3.03	27.05	1974	3.51	31.34
	1955	2.67	23.84	**1965**	3.17	28.30	**1975**	3.54	31.61
	1956	2.48	22.14	1966	3.18	28.39	1976	3.50	31.23
	1957	2.69	24.02	1967	3.31	29.55	*1980	3.52	31.39
	1958	2.85	25.45	1968	3.18	28.39	*1990	3.96	35.34
	1959	2.66	23.75	1969	3.16	28.21	*2000	4.37	38.96

*Mean of projected yields

Figure B-1.5

BRAZILIAN SOYBEAN YIELDS



Point A = 1972-76 Average = 23.2 bu/a = 1.5 tons/ha

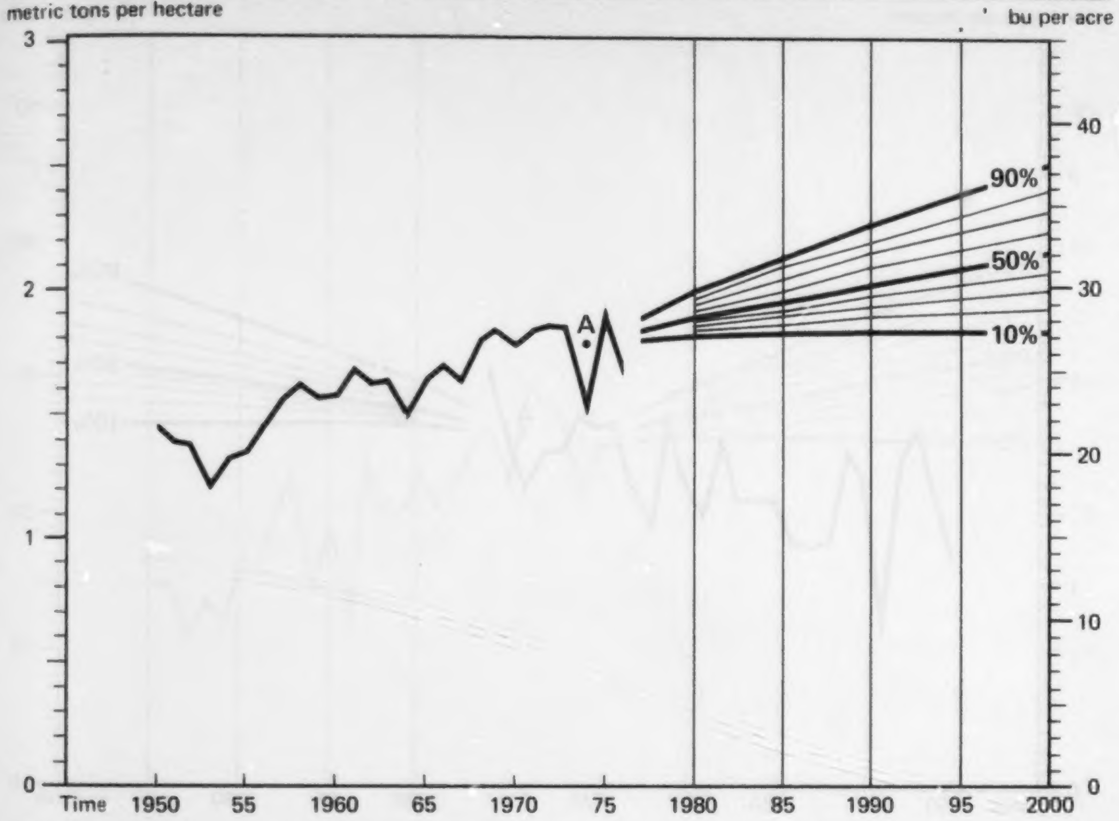
Note: Yield calculated on seeded area
Only limited quantities produced prior to 1966

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
BRAZILIAN SOYBEAN YIELDS	**1950**			**1960**	1.20	17.84	**1970**	1.14	16.95
	1951			1961	1.13	16.80	1971	1.21	17.99
	1952	1.30	19.33	1962	1.10	16.35	1972	1.45	21.56
	1953	1.40	20.82	1963	.95	14.12	1973	1.39	20.67
	1954	1.72	25.58	1964	.85	12.64	1974	1.53	22.75
	1955	1.44	21.41	**1965**	1.21	17.99	**1975**	1.70	25.28
	1956	1.42	21.11	1966	1.21	17.99	1976	1.72	25.58
	1957	1.25	18.59	1967	1.17	17.40	*1980	1.79	26.55
	1958	1.22	18.14	1968	.91	13.53	*1990	2.00	29.74
	1959	1.07	15.91	1969	1.17	17.40	*2000	2.18	32.49

*Mean of projected yields

Figure B-1.6

U.S. SOYBEAN YIELDS



Point A = 1972-76 Average = 26.6 bu/a = 1.7 tons/ha

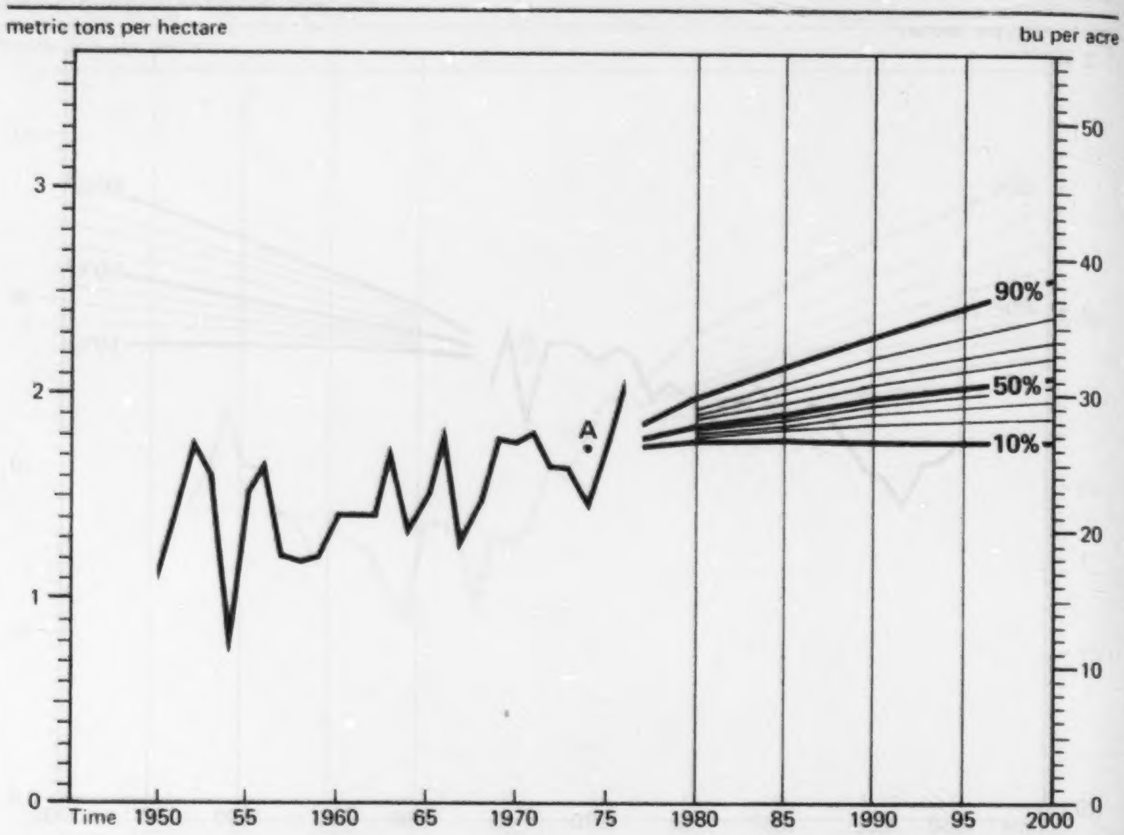
Note: Yield calculated on harvested area

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
U.S. SOYBEAN YIELDS	**1950**	1.46	21.7	**1960**	1.58	23.5	**1970**	1.79	26.7
	1951	1.40	20.8	1961	1.68	25.1	1971	1.85	27.5
	1952	1.39	20.7	1962	1.62	24.2	1972	1.87	27.8
	1953	1.22	18.2	1963	1.64	24.4	1973	1.86	27.7
	1954	1.32	19.7	1964	1.50	22.4	1974	1.58	23.2
	1955	1.35	20.1	**1965**	1.64	24.5	**1975**	1.93	28.8
	1956	1.46	21.8	1966	1.70	25.4	1976	1.72	25.6
	1957	1.56	23.2	1967	1.64	24.5	*1980	1.90	28.32
	1958	1.62	24.2	1968	1.80	26.8	*1990	2.05	30.49
	1959	1.57	23.4	1969	1.85	27.5	*2000	2.18	32.47

*Mean of Projected Yields

Figure B-1.7

CANADIAN WHEAT YIELDS



Point A = 1972-76 Average = 26.0 bu/a = 1.7 tons/ha

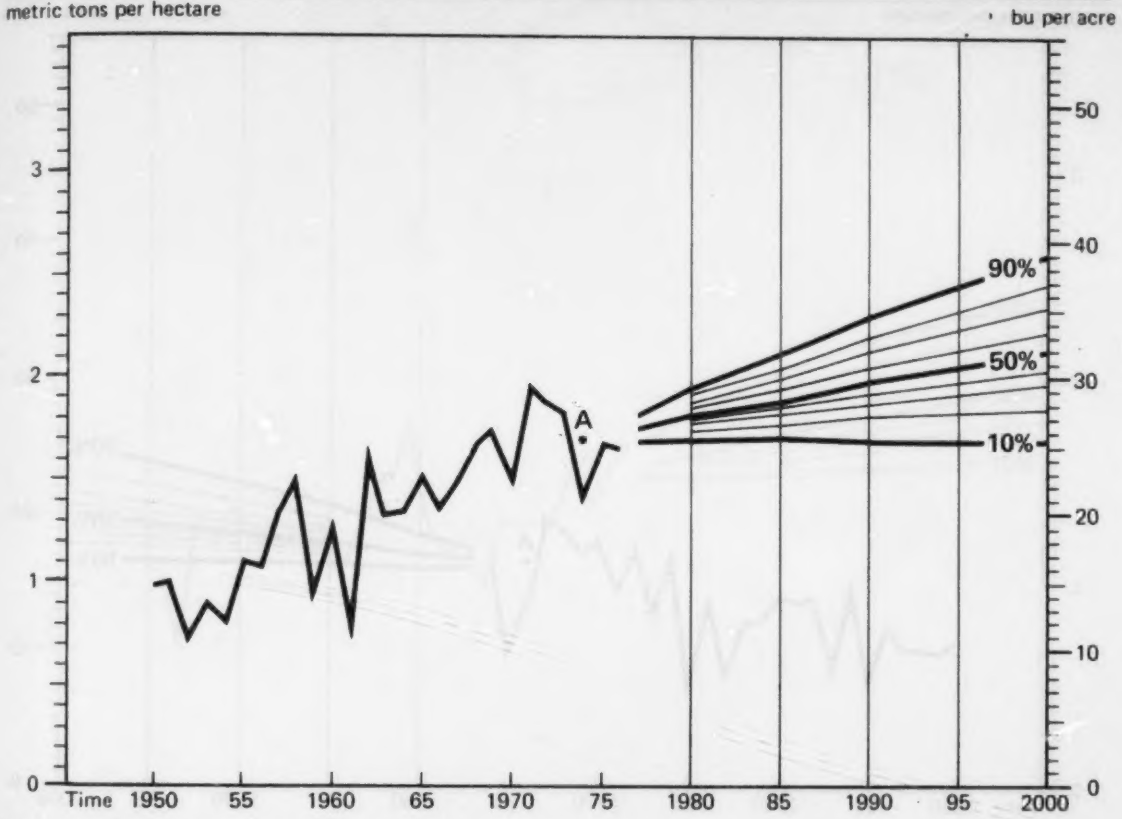
Note: Yield calculated on area harvested

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
	1950	1.15	17.09	**1960**	1.42	21.13	**1970**	1.79	26.57
CANADIAN	1951	1.47	21.93	1961	0.75	11.20	1971	1.84	27.29
WHEAT	1952	1.80	26.84	1962	1.42	21.10	1972	1.68	24.99
YIELD	1953	1.62	24.04	1963	1.76	26.25	1973	1.67	24.84
	1954	0.87	13.00	1964	1.36	20.24	1974	1.49	22.13
	1955	1.54	22.92	**1965**	1.54	22.95	**1975**	1.80	26.80
	1956	1.69	25.16	1966	1.87	27.87	1976	2.11	31.43
	1957	1.23	18.22	1967	1.32	19.69	*1980	1.89	28.09
	1958	1.21	17.98	1968	1.49	22.10	*1990	2.05	30.43
	1959	1.22	18.17	1969	1.80	26.90	*2000	2.17	32.24

*Mean of projected yields

Figure B-1.8

U.S. SPRING WHEAT YIELDS, SELECTED STATES[1]



Point A = 1972-76 Average = 25.7 bu/a = 1.7 tons/ha

Note: Yield calculated on seeded area

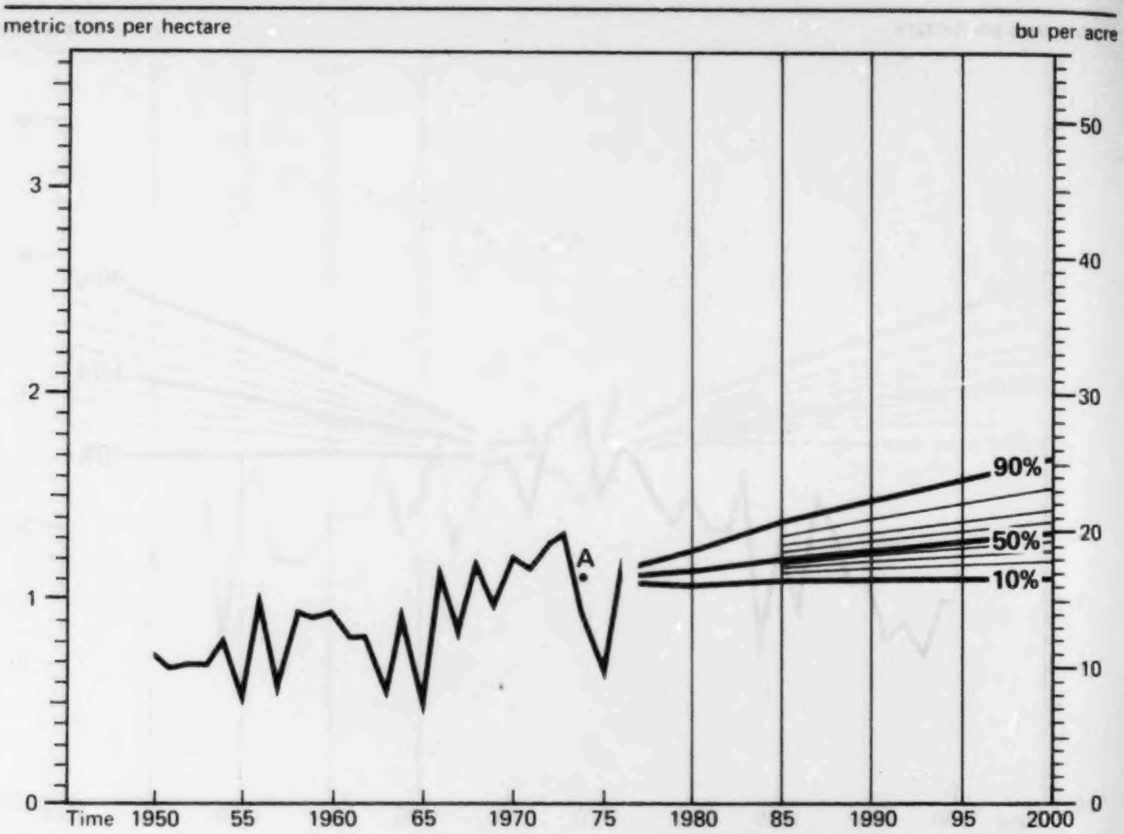
[1] Five states – Minnesota, North Dakota, South Dakota, Montana, and Idaho -- account for about 90 percent of spring wheat production.

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
	1950	1.02	15.1	**1960**	1.34	19.9	**1970**	1.55	23.1
U.S.	1951	1.03	15.3	1961	.88	13.1	1971	2.00	29.8
SPRING	1952	.76	11.3	1962	1.68	25.0	1972	1.90	28.3
WHEAT	1953	.93	13.9	1963	1.35	20.1	1973	1.86	27.7
YIELDS	1954	.83	12.4	1964	1.37	20.4	1974	1.47	21.9
	1955	1.14	16.9	**1965**	1.56	23.2	**1975**	1.71	25.5
	1956	1.10	16.4	1966	1.40	20.8	1976	1.69	25.1
	1957	1.36	20.3	1967	1.54	22.9	*1980	1.85	27.5
	1958	1.55	23.0	1968	1.70	25.3	*1990	2.02	30.0
	1959	1.02	15.1	1969	1.78	26.5	*2000	2.18	32.4

*Mean of projected yields

Figure B-1.9

USSR SPRING WHEAT YIELDS



Point A = 1972-76 Average = 16.5 bu/a =1.1 tons/ha

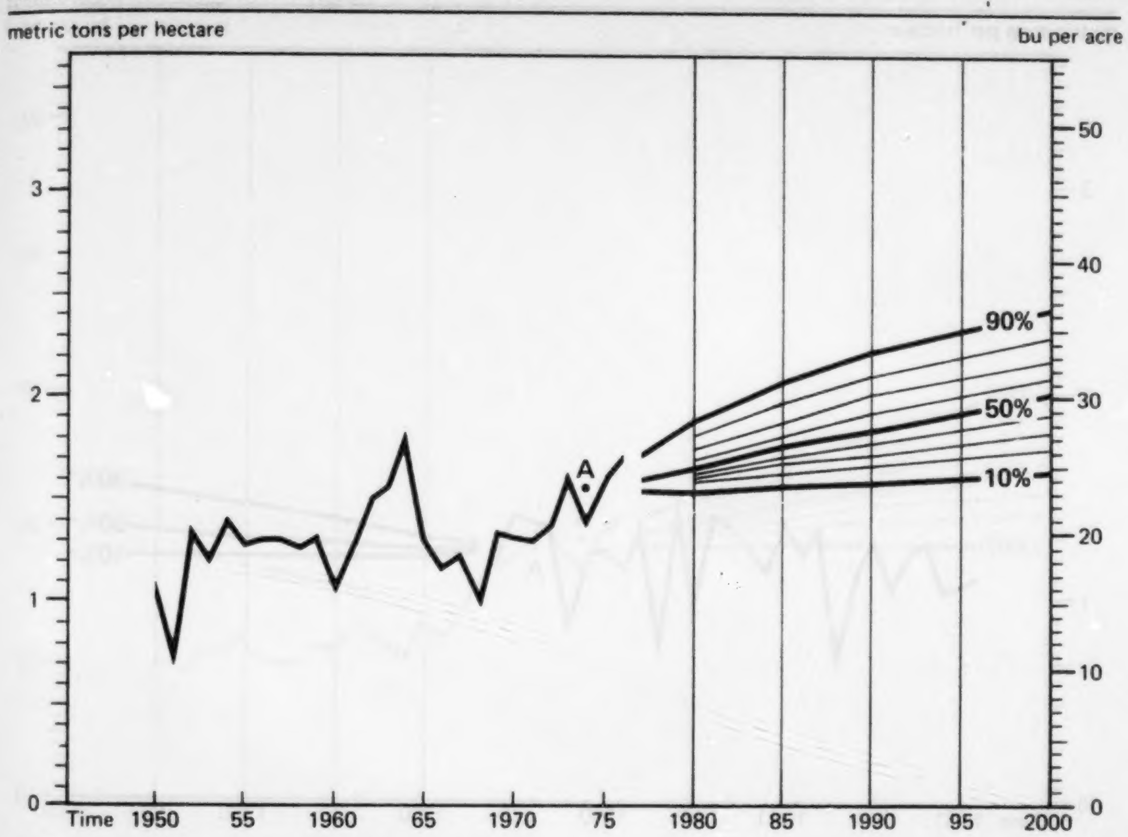
Note: Yield calculated on area seeded, adjusted for diversions for other uses.

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
USSR SPRING WHEAT YIELDS	**1950**	.76	11.30	**1960**	.95	14.13	**1970**	1.23	18.30
	1951	.68	10.11	1961	.82	12.20	1971	1.18	17.55
	1952	.70	10.41	1962	.82	12.20	1972	1.30	19.34
	1953	.70	10.41	1963	.59	8.78	1973	1.35	20.08
	1954	.83	12.35	1964	.99	14.73	1974	.95	14.13
	1955	.54	8.03	**1965**	.55	8.18	**1975**	.70	10.41
	1956	1.07	15.92	1966	1.20	17.85	1976	1.24	18.44
	1957	.61	9.07	1967	.89	13.24	*1980	1.17	17.44
	1958	.97	14.43	1968	1.22	18.15	*1990	1.29	19.18
	1959	.94	13.98	1969	.99	15.02	*2000	1.39	20.64

*Mean of projected yields

Figure B-1.10

ARGENTINE WHEAT YIELDS



Point A = 1972-76 Average = 23.3 bu/a = 1.5 tons/ha

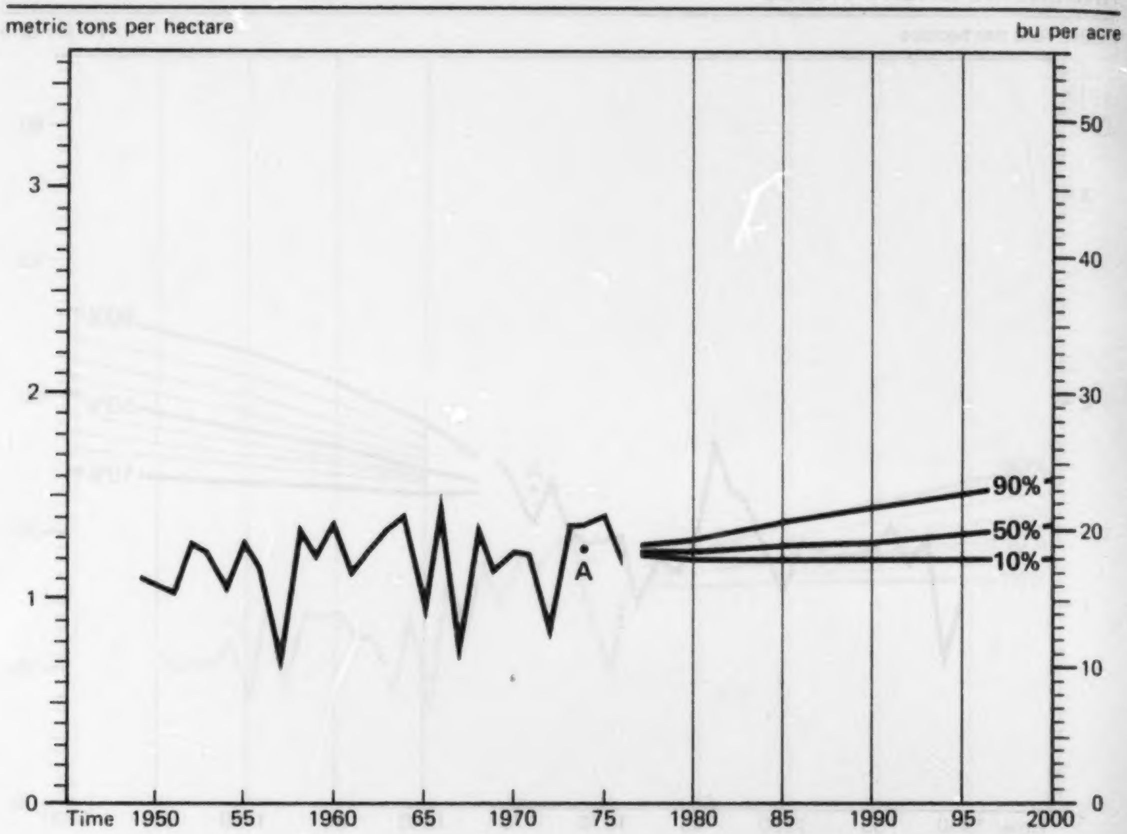
Yield calculated on area harvested

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
ARGENTINE WHEAT YIELDS	**1950**	1.11	16.54	**1960**	1.10	16.39	**1970**	1.33	19.82
	1951	0.77	11.47	1961	1.30	19.37	1971	1.32	19.67
	1952	1.37	20.41	1962	1.52	22.65	1972	1.39	20.71
	1953	1.24	18.48	1963	1.58	23.54	1973	1.66	24.73
	1954	1.41	21.01	1964	1.84	27.42	1974	1.41	21.01
	1955	1.29	19.22	**1965**	1.32	19.67	**1975**	1.63	24.29
	1956	1.32	19.67	1966	1.20	17.88	1976	1.74	25.93
	1957	1.32	19.67	1967	1.26	18.77	*1980	1.70	25.35
	1958	1.28	19.07	1968	0.98	14.60	*1990	1.90	28.29
	1959	1.33	19.82	1969	1.35	20.12	*2000	2.07	30.82

*Mean of projected yields

Figure B-1.11

AUSTRALIAN WHEAT YIELDS



Point A = 1972-76 Average = 18.7 bu/a = 1.2 tons/ha

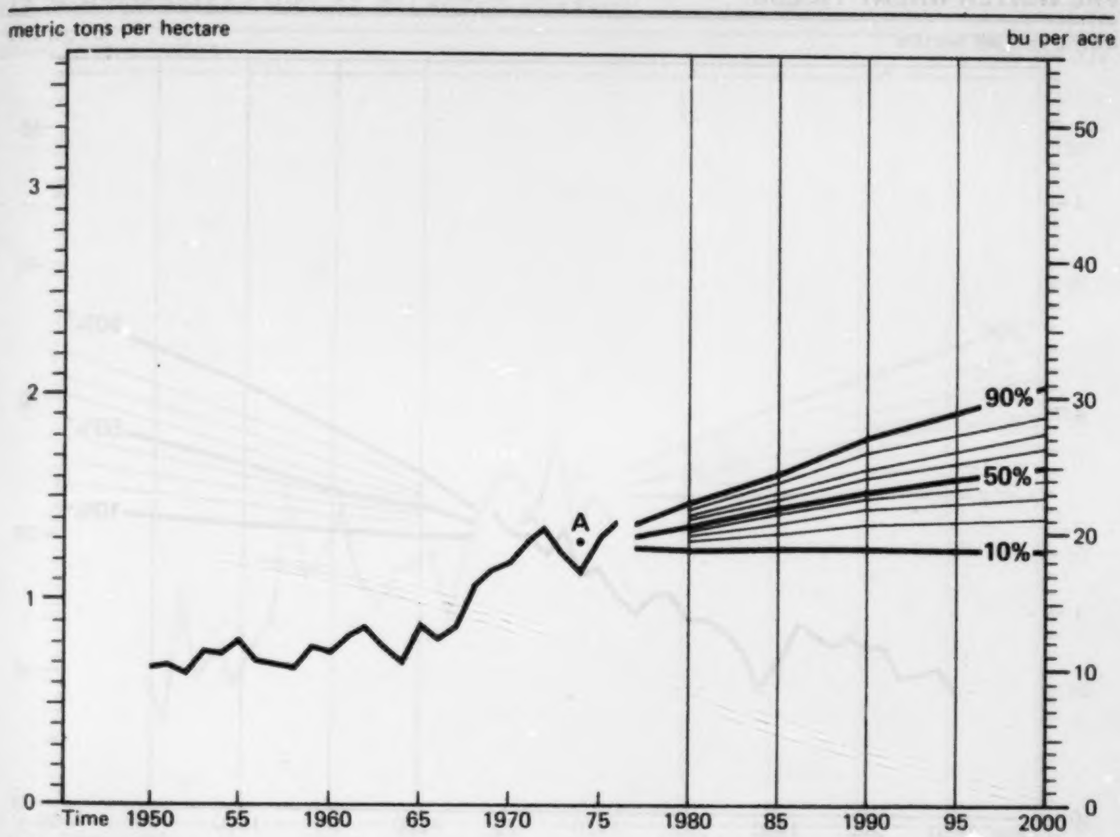
Note: Yield calculated on area seeded

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
AUSTRALIAN WHEAT YIELDS	**1950**	1.08	16.09	**1960**	1.40	20.86	**1970**	1.24	18.48
	1951	1.06	15.79	1961	1.16	17.28	1971	1.23	18.33
	1952	1.30	19.37	1962	1.27	18.92	1972	.90	13.41
	1953	1.25	18.63	1963	1.36	20.26	1973	1.37	20.41
	1954	1.08	16.09	1964	1.41	21.01	1974	1.38	20.56
	1955	1.31	19.52	**1965**	1.02	15.20	**1975**	1.41	21.01
	1956	1.16	17.28	1966	1.53	22.80	1976	1.21	18.03
	1957	.76	11.32	1967	.86	12.81	*1980	1.25	18.64
	1958	1.37	20.41	1968	1.39	20.71	*1990	1.32	19.61
	1959	1.24	18.48	1969	1.15	17.14	*2000	1.40	20.76

*Mean of projected yields

Figure B-1.12

INDIAN WHEAT YIELDS



Point A = 1972-76 Average = 19.5 bu/a = 1.3 tons/ha

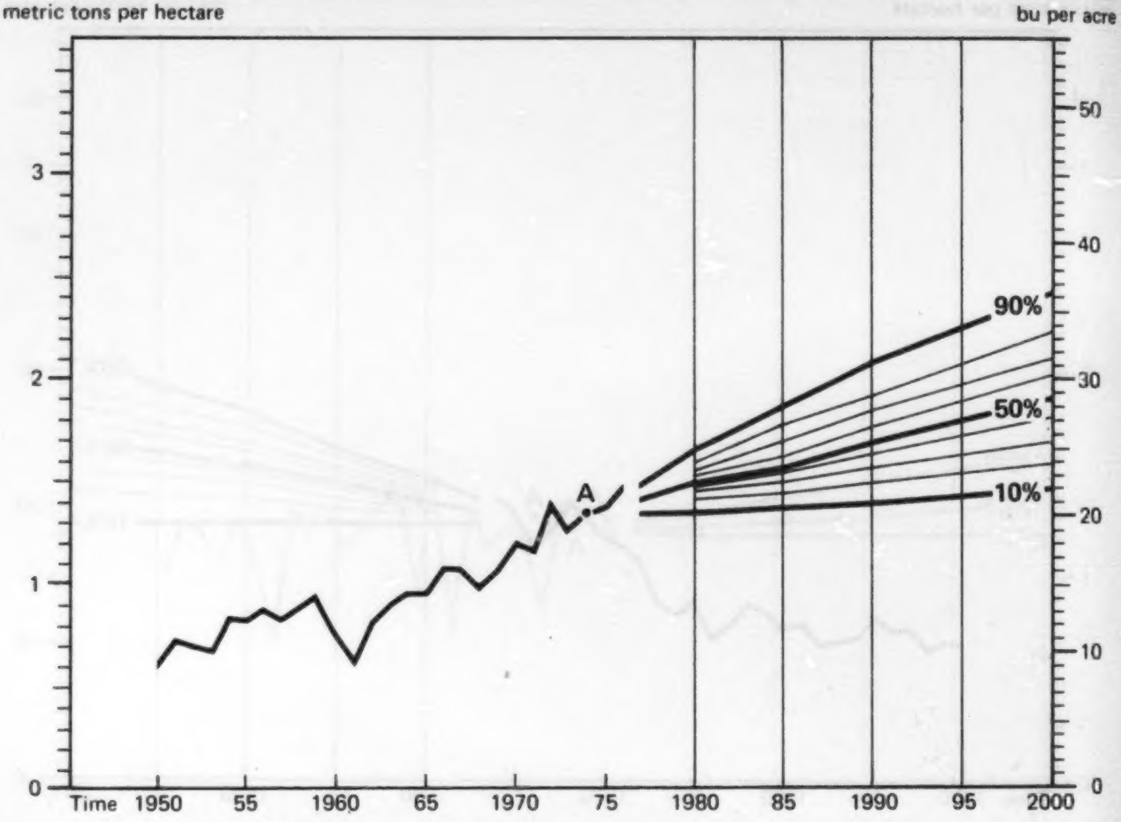
Note: Yield calculated on area harvested.

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
	1950	.69	10.26	**1960**	.77	11.45	**1970**	1.21	18.00
INDIAN WHEAT YIELDS	1951	.70	10.41	1961	.85	12.64	1971	1.31	19.49
	1952	.67	9.97	1962	.89	13.24	1972	1.38	20.53
	1953	.77	11.45	1963	.79	11.75	1973	1.27	18.89
	1954	.76	11.30	1964	.73	10.86	1974	1.17	17.40
	1955	.81	12.05	**1965**	.91	13.54	**1975**	1.34	19.93
	1956	.72	10.71	1966	.83	12.35	1976	1.41	20.97
	1957	.70	10.41	1967	.89	13.24	*1980	1.39	20.69
	1958	.68	10.11	1968	1.10	16.36	*1990	1.56	23.27
	1959	.79	11.75	1969	1.17	17.40	*2000	1.70	25.21

*Mean of projected yields

Figure B-1.13

PRC WINTER WHEAT YIELDS



Point A = 1972-76 Average = 20.8 bu/a =1.4 tons/ha

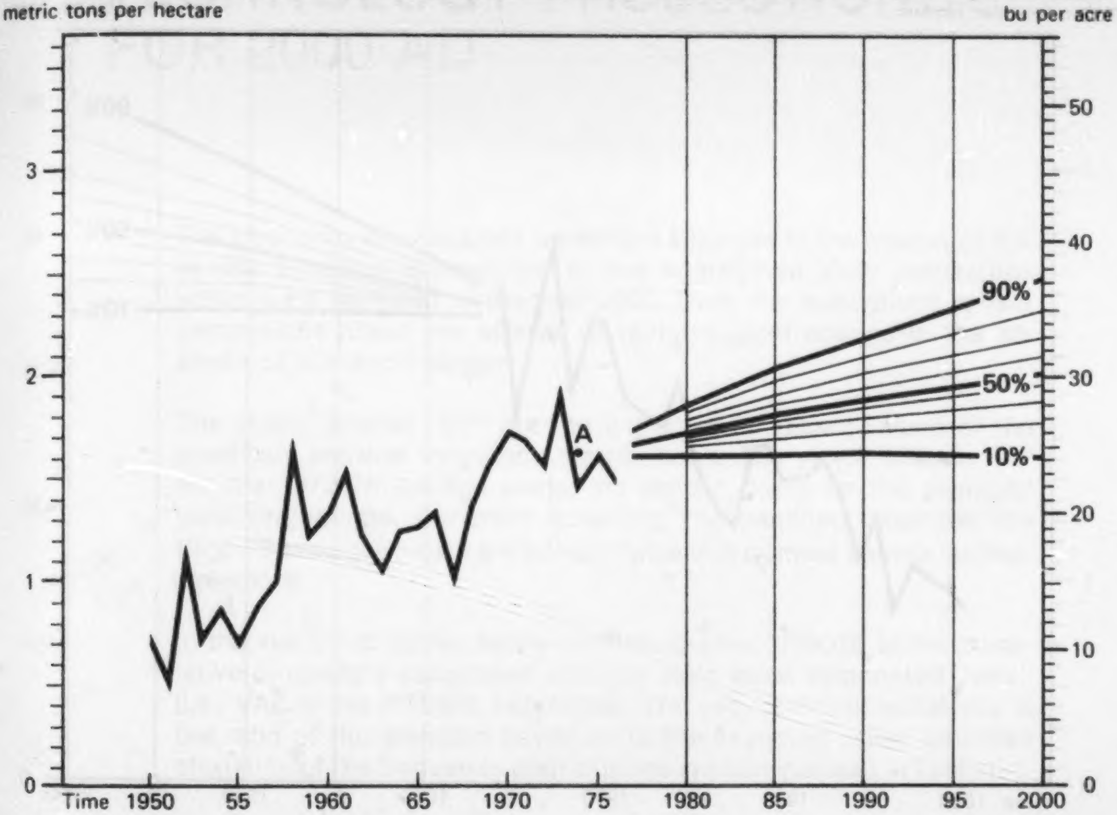
Note: Yield calculated on area harvested

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
	1950	.64	09.54	**1960**	0.78	11.62	**1970**	1.22	18.18
PRC WHEAT YIELD DATA	1951	.75	11.18	1961	0.65	9.69	1971	1.19	17.73
	1952	.73	10.88	1962	0.84	12.52	1972	1.43	21.31
	1953	.71	10.58	1963	0.93	13.86	1973	1.30	19.37
	1954	.87	12.96	1964	0.99	14.75	1974	1.36	20.26
	1955	.86	12.81	**1965**	0.99	14.75	**1975**	1.40	20.86
	1956	.91	13.56	1966	1.11	16.54	1976	1.50	22.31
	1957	.86	12.81	1967	1.11	16.54	*1980	1.53	22.70
	1958	.93	13.86	1968	1.02	15.20	*1990	1.74	25.89
	1959	.98	14.60	1969	1.08	16.09	*2000	1.95	28.96

*Mean of projected yields

Figure B-1.14

U.S. WINTER WHEAT YIELDS, SELECTED STATES[1]



Point A = 1972-76 Average = 24.5 bu/a = 1.6 tons/ha

Note: Yield calculated on area harvested

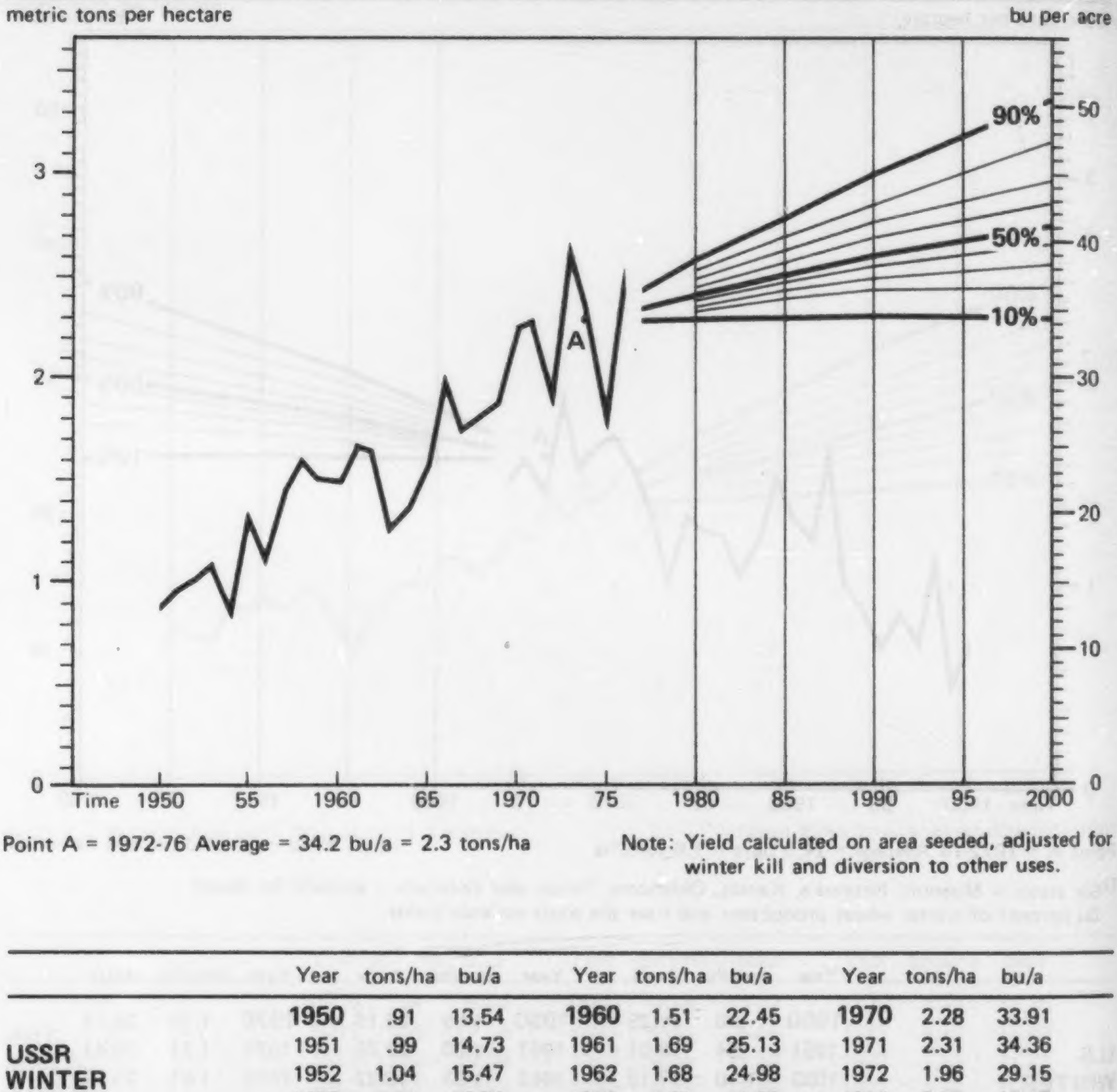
[1] Six states – Missouri, Nebraska, Kansas, Oklahoma, Texas, and Colorado -- account for about 50 percent of winter wheat production and have the most variable yields.

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
	1950	.76	11.25	**1960**	1.69	25.15	**1970**	1.76	26.11
U.S. WINTER WHEAT YIELDS	1951	.54	8.01	1961	1.60	23.79	1971	1.71	25.41
	1952	1.15	17.18	1962	1.23	18.27	1972	1.61	23.91
	1953	.75	11.13	1963	1.08	16.06	1973	1.99	29.58
	1954	.88	13.16	1964	1.27	18.90	1974	1.50	22.29
	1955	.73	10.88	**1965**	1.28	19.11	**1975**	1.65	24.48
	1956	.88	13.04	1966	1.35	20.10	1976	1.50	22.35
	1957	1.01	15.07	1967	1.07	15.94	*1980	2.45	36.49
	1958	1.73	25.69	1968	1.40	20.86	*1990	2.66	39.60
	1959	1.26	18.80	1969	1.61	23.94	*2000	2.83	42.04

*Mean of projected yields

Figure B-1.15

USSR WINTER WHEAT YIELDS



Point A = 1972-76 Average = 34.2 bu/a = 2.3 tons/ha

Note: Yield calculated on area seeded, adjusted for winter kill and diversion to other uses.

	Year	tons/ha	bu/a	Year	tons/ha	bu/a	Year	tons/ha	bu/a
	1950	.91	13.54	**1960**	1.51	22.45	**1970**	2.28	33.91
USSR WINTER WHEAT YIELDS	1951	.99	14.73	1961	1.69	25.13	1971	2.31	34.36
	1952	1.04	15.47	1962	1.68	24.98	1972	1.96	29.15
	1953	1.11	16.51	1963	1.30	19.33	1973	2.70	40.16
	1954	.93	13.83	1964	1.38	20.52	1974	2.40	35.70
	1955	1.35	20.08	**1965**	1.61	23.94	**1975**	1.87	27.82
	1956	1.16	17.25	1966	2.04	30.33	1976	2.58	38.38
	1957	1.47	21.87	1967	1.78	26.47	*1980	2.45	36.49
	1958	1.62	24.10	1968	1.83	27.21	*1990	2.66	39.60
	1959	1.52	22.61	1969	1.89	28.10	*2000	2.83	42.04

*Mean of projected yields

APPENDIX B–2

TECHNOLOGY PROJECTIONS FOR 2000 AD

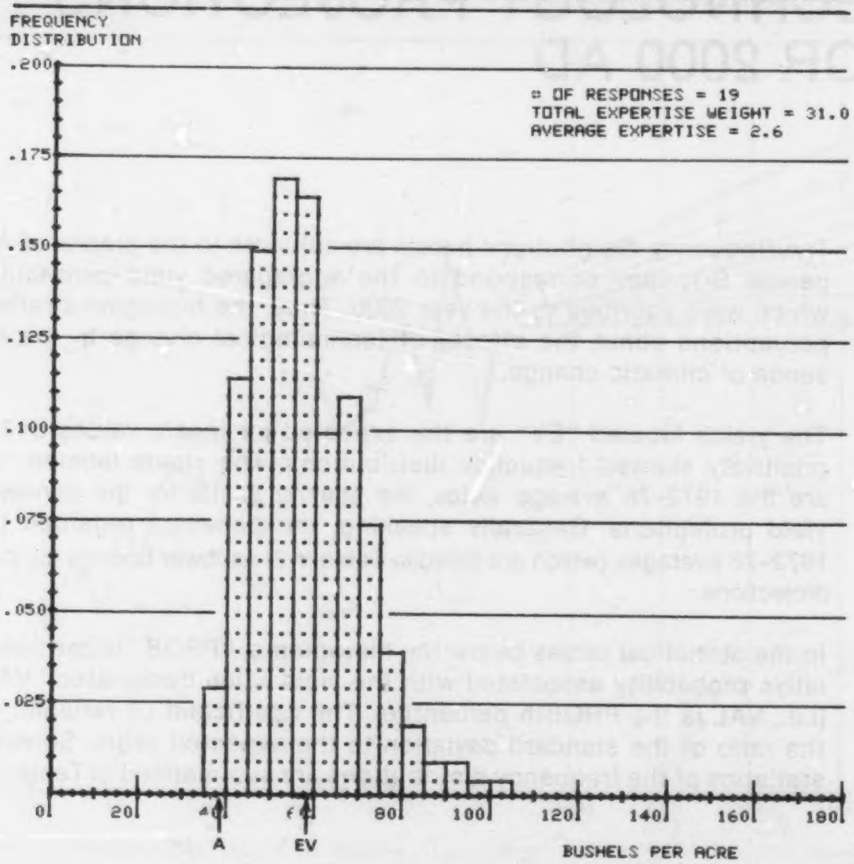
The frequency distributions herein are adjuncts to the graphs of Appendix B-1; they correspond to the aggregated yield percentiles which were ascribed to the year 2000. Thus, the histograms reflect perceptions about the effects of technological change in the absence of climatic change.

The yields labeled "EV" are the expected (or mean) values of the positively skewed frequency distributions. The yields labeled "A" are the 1972–76 average yields, the starting points for the panelists' yield projections. Generally speaking, the panelists regarded the 1972–76 averages (which are listed in Table V-2) as lower bounds for their projections.

In the statistical tables below the histograms, "PROB" is the cumulative probability associated with the yield value designated "VAL" (i.e., VAL is the PROBth percentile). The coefficient of variability is the ratio of the standard deviation to the expected value. Selected statistics of the frequency distributions are summarized in Table II-1.

Figure B-2.1

ARGENTINE CORN YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES

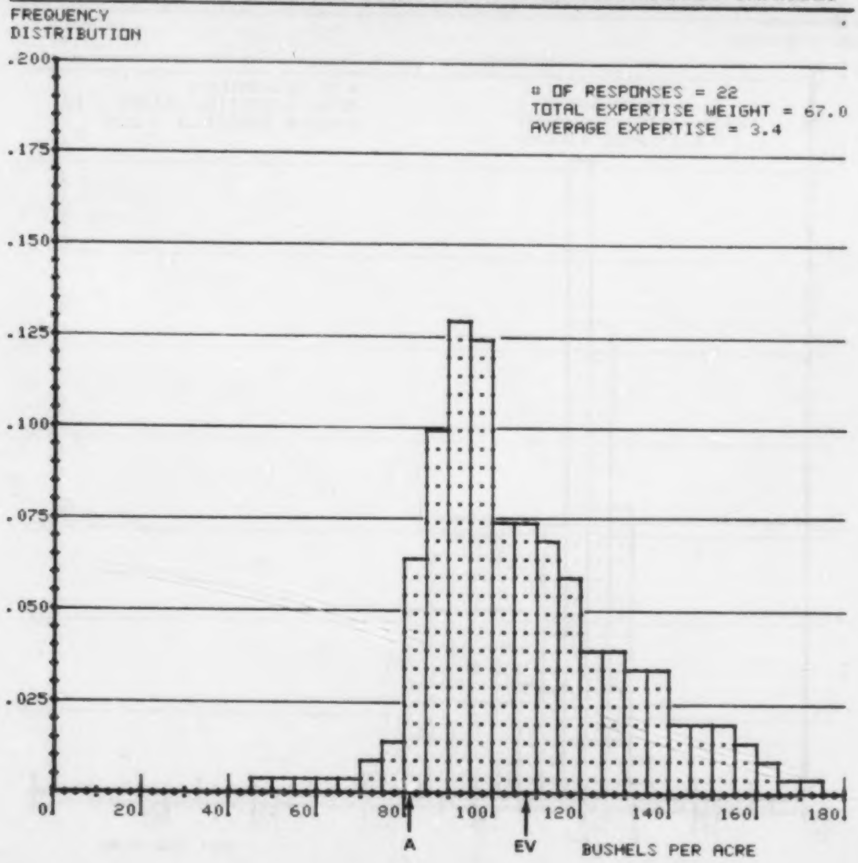


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

          PROB  VAL   PROB  VAL   PROB  VAL   PROB  VAL
             0  34.3     5  41.2    10  43.5    15  45.1
            20  46.7    25  48.3    30  50.1    35  51.8
            40  53.2    45  54.6    50  56.0    55  57.4
            60  59.0    65  60.8    70  63.2    75  66.5
            80  68.7    85  70.7    90  74.0    95  80.4
           100 105.5

           VAL  PROB   VAL  PROB   VAL  PROB   VAL  PROB   VAL  PROB
            5.   0.0   10.   0.0   15.   0.0   20.   0.0   25.   0.0
           30.   0.0   35.   0.1   40.   3.2   45.  14.6   50.  29.8
           55.  46.5   60.  62.9   65.  72.7   70.  83.5   75.  90.8
           80.  94.7   85.  97.0   90.  98.0   95.  98.8  100.  99.4
          105.  99.9  110. 100.0
```

```
EXPECTED VALUE =  57.92
STANDARD DEVIATION =  12.53
COEFFICIENT OF VARIABILITY =  .2163
SKEWNESS =    0.81
TOTAL PROBABILITY =1.000
THE AVERAGE 1972/76 YIELD IS 38.4 BUS./ACRE (2.41 TONS/HA.)
```

Figure B-2.2

U.S. CORN YIELDS, SELECTED STATES
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES

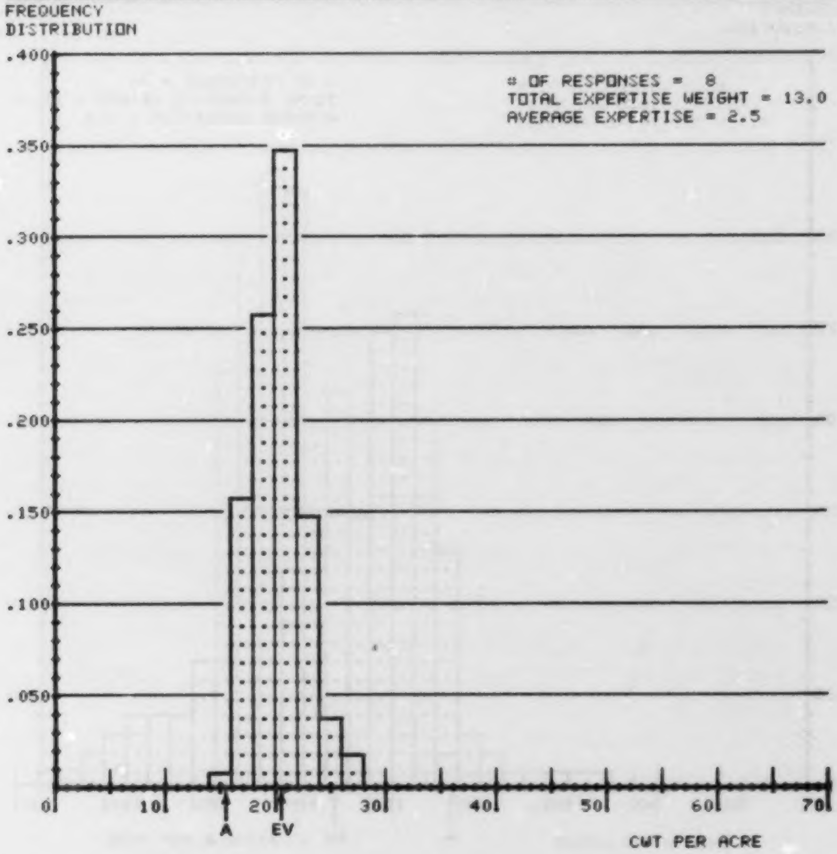


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

       PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL
          0  41.4    5  80.5   10  84.2   15  87.2
         20  89.5   25  91.7   30  93.4   35  95.3
         40  97.2   45  99.2   50 102.1   55 105.5
         60 108.7   65 112.0   70 115.7   75 120.1
         80 126.1   85 132.7   90 140.0   95 152.0
        100 173.9

        VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB
         5.   0.0  10.   0.0  15.   0.0  20.   0.0  25.   0.0
        30.   0.0  35.   0.0  40.   0.0  45.   0.2  50.   0.4
        55.   0.7  60.   1.0  65.   1.3  70.   2.0  75.   3.0
        80.   4.6  85.  11.3  90.  21.1  95.  34.2 100.  46.6
       105.  54.3 110.  61.9 115.  69.1 120.  74.9 125.  79.1
       130.  83.0 135.  86.7 140.  90.0 145.  92.1 150.  94.2
       155.  96.2 160.  97.7 165.  98.7 170.  99.4 175. 100.0
```

```
EXPECTED VALUE = 107.32
STANDARD DEVIATION =  22.40
COEFFICIENT OF VARIABILITY =  .2087
@SKEWNESS =   0.64
TOTAL PROBABILITY =1.000
THE AVERAGE 1972/76 YIELD IS 81.4 BUS./ACRE (5.11 TONS/HA.)
```

Figure B-2.3

INDIAN RICE YIELDS (PADDY)
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES



CUMULATIVE PROBABILITY AND RELATED STATISTICS

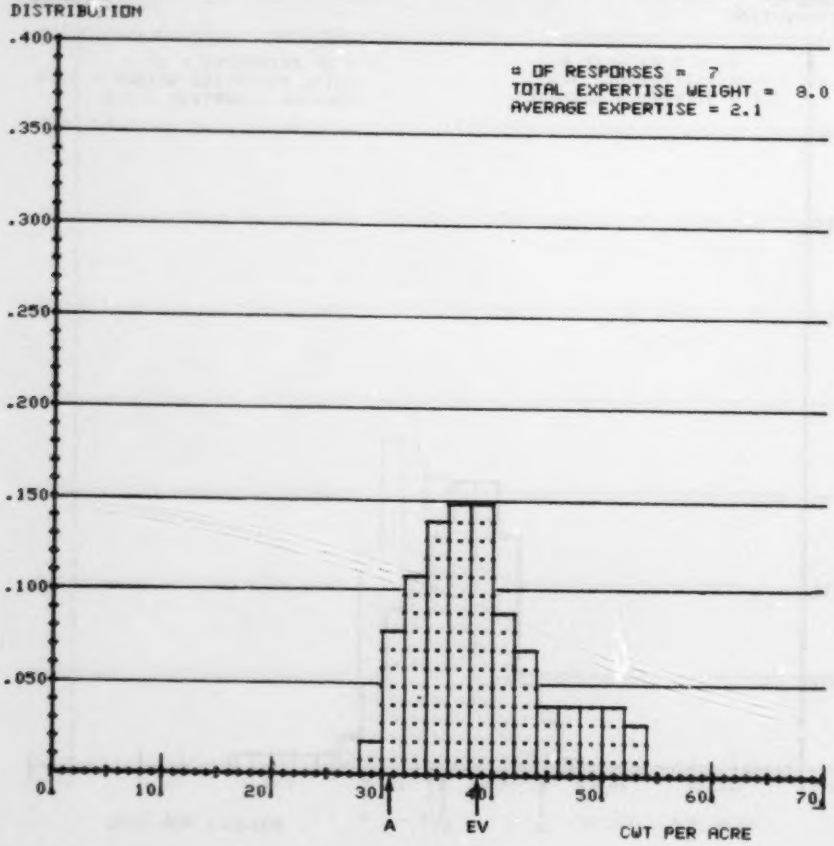
PROB	VAL	PROB	VAL	PROB	VAL	PROB	VAL
0	15.2	5	16.8	10	17.4	15	17.8
20	18.2	25	18.5	30	18.9	35	19.3
40	19.8	45	20.1	50	20.4	55	20.6
60	20.9	65	21.2	70	21.5	75	21.8
80	22.1	85	22.4	90	23.0	95	24.3
100	27.8						

VAL	PROB	VAL	PROB	VAL	PROB	VAL	PROB	VAL	PROB
2.	0.0	4.	0.0	6.	0.0	8.	0.0	10.	0.0
12.	0.0	14.	0.0	16.	1.5	18.	17.7	20.	43.5
22.	79.0	24.	94.5	26.	98.4	28.	100.0		

EXPECTED VALUE = 20.30
STANDARD DEVIATION = 2.25
COEFFICIENT OF VARIABILITY = .1108
SKEWNESS = 0.32
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 15.2 CWT/ACRE (1.71 TONS/HA.)

Figure B-2.4

PRC RICE YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES'

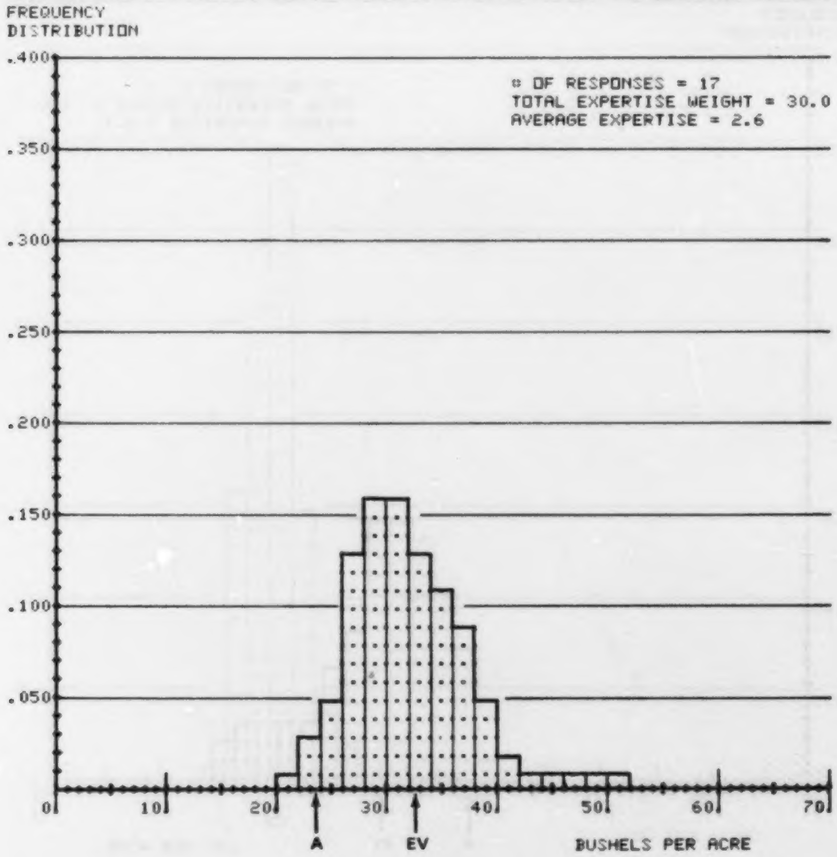


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

           PROB  VAL  PROB   VAL  PROB   VAL  PROB   VAL
              0  29.3    5  31.0    10  32.2    15  33.1
             20  33.9   25  34.6    30  35.4    35  36.0
             40  36.7   45  37.3    50  38.0    55  38.6
             60  39.3   65  40.0    70  41.0    75  42.3
             80  43.6   85  45.7    90  48.3    95  50.8
            100  53.4

        -   VAL  PROB  VAL  PROB   VAL  PROB   VAL  PROB  VAL  PROB
             2.   0.0   4.   0.0    6.   0.0    8.   0.0  10.   0.0
            12.   0.0  14.   0.0   16.   0.0   18.   0.0  20.   0.0
            22.   0.0  24.   0.0   26.   0.0   28.   0.0  30.   1.8
            32.   9.3  34.  20.4   36.  34.6   38.  50.1  40.  65.1
            42.  73.9  44.  81.2   46.  85.6   48.  89.5  50.  93.5
            52.  97.4  54. 100.0
```

```
EXPECTED VALUE =  38.96
STANDARD DEVIATION =   5.77
COEFFICIENT OF VARIABILITY =  .1482
SKEWNESS =    0.66
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 30.7 CWT/ACRE (3.42 TONS/HA.)
```

Figure B-2.5

BRAZILIAN SOYBEAN YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES

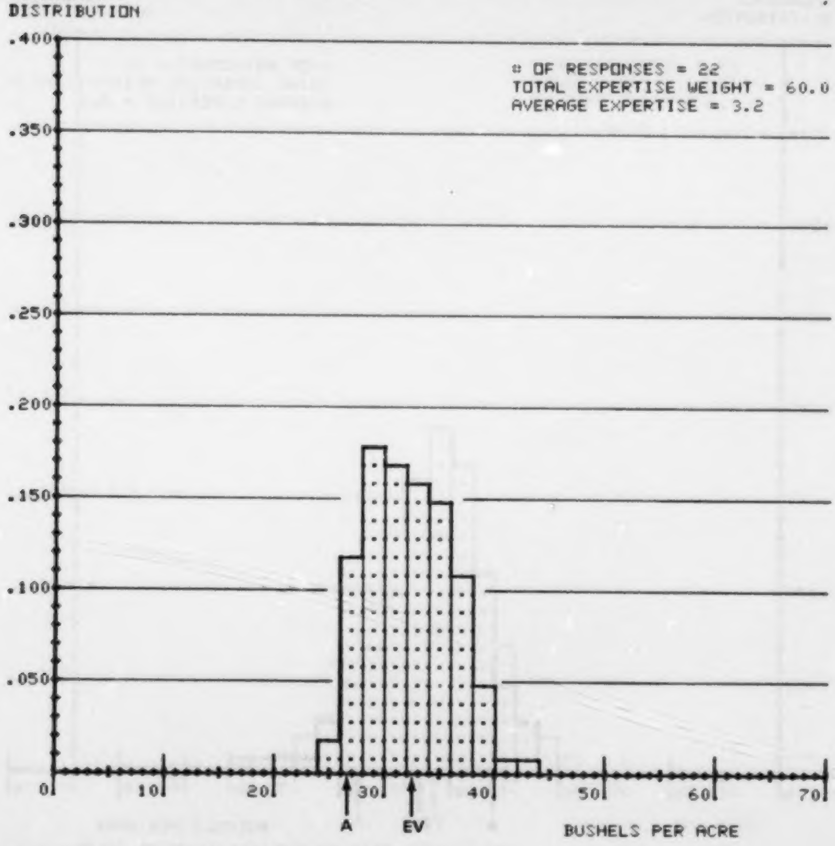


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

          PROB   VAL   PROB   VAL   PROB   VAL   PROB   VAL
             0  21.2      5  24.7     10  26.3     15  27.1
            20  27.8     25  28.4     30  29.1     35  29.7
            40  30.3     45  30.9     50  31.6     55  32.3
            60  33.0     65  33.8     70  34.6     75  35.5
            80  36.6     85  37.6     90  38.8     95  43.5
           100  66.1

           VAL   PROB   VAL   PROB   VAL   PROB   VAL   PROB   VAL   PROB
            2.    0.0    4.    0.0    6.    0.0    8.    0.0   10.    0.0
           12.    0.0   14.    0.0   16.    0.0   18.    0.0   20.    0.0
           22.    0.6   24.    3.6   26.    8.8   28.   21.6   30.   37.2
           32.   53.1   34.   66.6   36.   77.5   38.   86.9   40.   92.1
           42.   94.1   44.   95.3   46.   96.3   48.   97.3   50.   98.3
           52.   99.0   54.   99.2   56.   99.3   58.   99.5   60.   99.6
           62.   99.7   64.   99.9   66.  100.0
```

```
EXPECTED VALUE =  32.49
STANDARD DEVIATION =    5.96
COEFFICIENT OF VARIABILITY =  .1835
SKEWNESS =   1.41
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 23.2 BUS./ACRE (1.56 TONS/HA.)
```

Figure B-2.6

U.S. SOYBEAN YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES

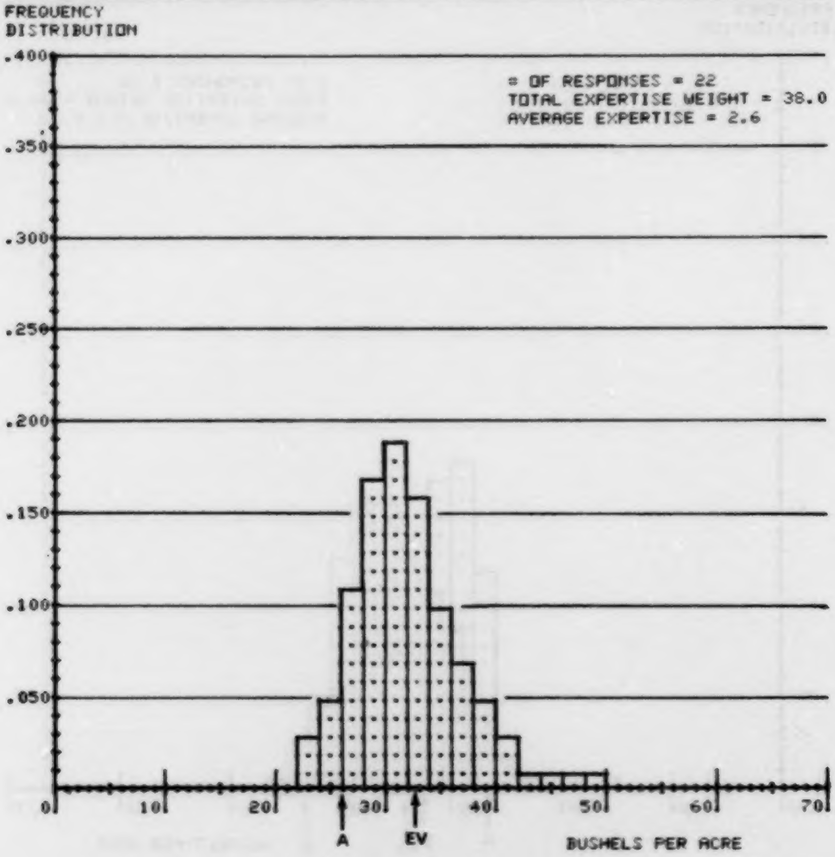


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

         PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL
            0  24.5    5  26.9   10  27.5   15  28.1
           20  28.8   25  29.3   30  29.8   35  30.3
           40  30.9   45  31.5   50  32.1   55  32.7
           60  33.3   65  33.9   70  34.6   75  35.2
           80  35.9   85  36.7   90  37.6   95  39.1
          100  48.3

          VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB
           2.   0.0   4.   0.0   6.   0.0   8.   0.0  10.   0.0
          12.   0.0  14.   0.0  16.   0.0  18.   0.0  20.   0.0
          22.   0.0  24.   0.0  26.   1.8  28.  14.2  30.  31.9
          32.  49.2  34.  65.5  36.  80.5  38.  91.5  40.  96.3
          42.  97.8  44.  99.0  46.  99.4  48.  99.9  50. 100.0
```

```
EXPECTED VALUE =  32.47
STANDARD DEVIATION =   4.06
COEFFICIENT OF VARIABILITY =  .1249
SKEWNESS =   0.62
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 26.6 BUS./ACRE (1.79 TONS/HA.)
```

Figure B-2.7

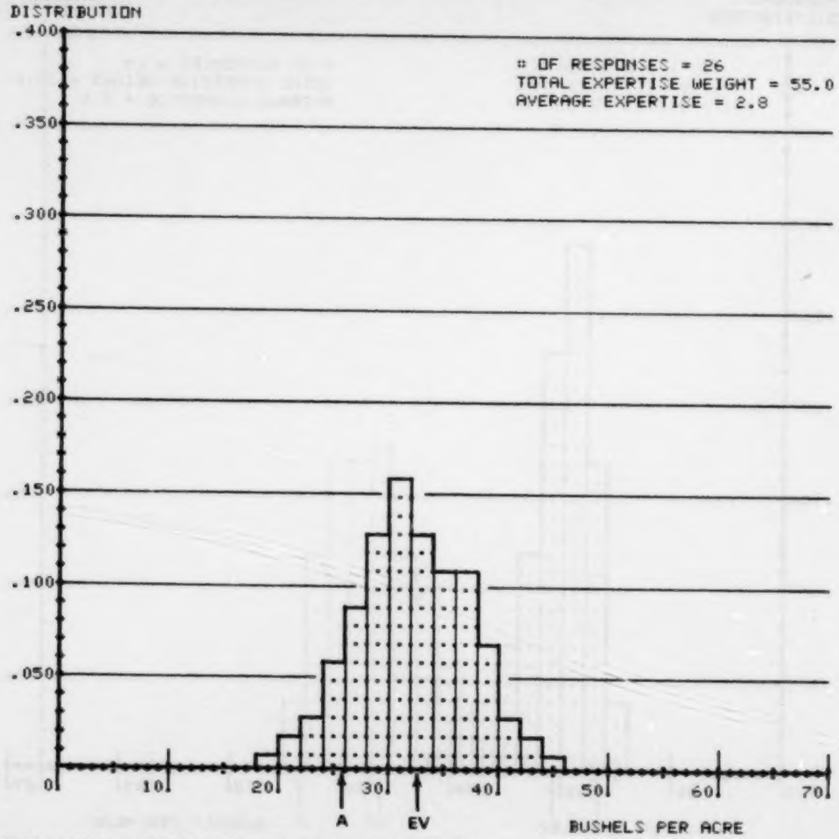
CANADIAN WHEAT YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES



```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

      PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL
         0  22.2    5  25.1   10  26.7   15  27.6
        20  28.3   25  29.0   30  29.6   35  30.0
        40  30.5   45  30.9   50  31.5   55  32.2
        60  32.8   65  33.3   70  34.0   75  34.7
        80  35.8   85  37.1   90  38.8   95  41.3
       100  50.3

       VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB.
        2.   0.0  4.    0.0  6.    0.0  8.    0.0  10.   0.0
       12.   0.0  14.   0.0  16.   0.0  18.   0.0  20.   0.0
       22.   0.0  24.   2.7  26.   7.4  28.  17.9  30.  34.5
       32.  53.8  34.  70.2  36.  80.6  38.  87.7  40.  93.0
       42.  95.8  44.  97.2  46.  98.2  48.  99.0  50.  99.9
       52. 100.0

EXPECTED VALUE =  32.24
STANDARD DEVIATION =   4.93
COEFFICIENT OF VARIABILITY =  .1529
SKEWNESS =   0.82
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 26.0 BUS./ACRE (1.75 TONS/HA.)
```

Figure B-2-8

U.S. SPRING WHEAT YIELDS, SELECTED STATES
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES



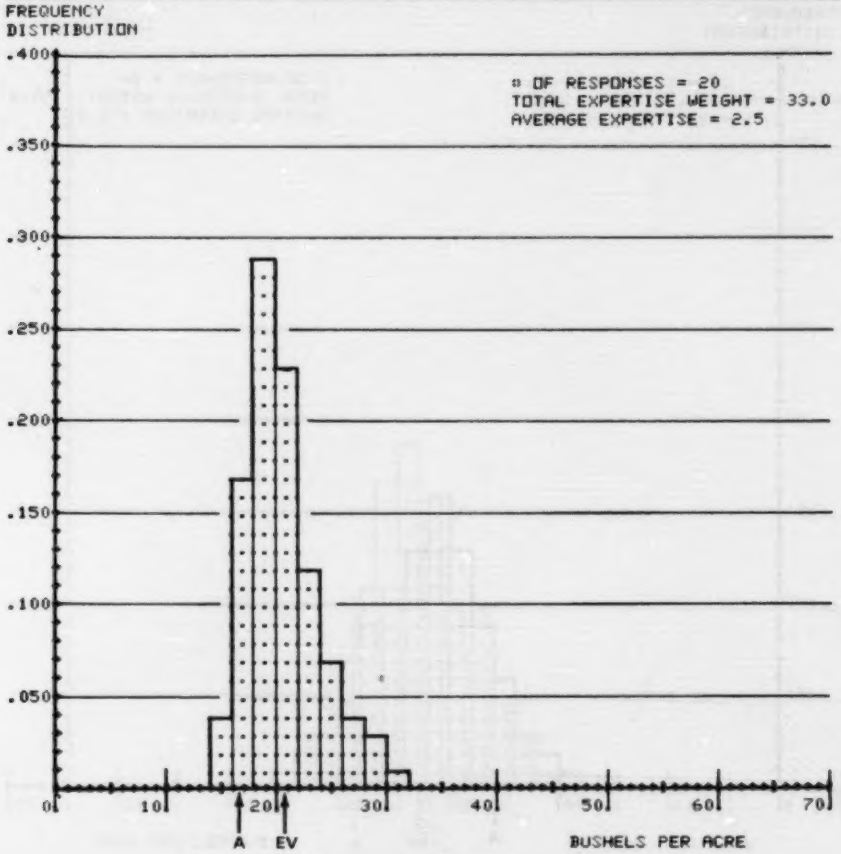
CUMULATIVE PROBABILITY AND RELATED STATISTICS

```
PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL
   0  18.6    5  23.6   10  25.6   15  26.9
  20  27.9   25  28.8   30  29.5   35  30.1
  40  30.7   45  31.4   50  32.1   55  32.8
  60  33.5   65  34.4   70  35.3   75  36.1
  80  37.0   85  37.9   90  39.1   95  41.3
 100  51.2

 VAL   PROB  VAL   PROB  VAL   PROB  VAL   PROB  VAL   PROB
  2.    0.0   4.    0.0   6.    0.0   8.    0.0  10.    0.0
 12.    0.0  14.    0.0  16.    0.0  18.    0.0  20.    0.7
 22.    2.4  24.    5.6  26.   11.7  28.   20.5  30.   33.9
 32.   49.5  34.   62.9  36.   74.3  38.   85.5  40.   92.8
 42.   96.2  44.   98.3  46.   99.2  48.   99.7  50.   99.9
 52.  100.0  54.  100.0  56.  100.0  58.  100.0  60.  100.0
 62.  100.0  64.  100.0  66.  100.0  68.  100.0  70.  100.0
 72.  100.0  74.  100.0  76.  100.0  78.  100.0  80.  100.0
```

```
EXPECTED VALUE =  32.35
STANDARD DEVIATION =    5.32
COEFFICIENT OF VARIABILITY =  .1645
SKEWNESS =    0.15
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 25.7 BUS./ACRE (1.73 TONS/HA.)
```

Figure B-2.9

USSR SPRING WHEAT YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES



CUMULATIVE PROBABILITY AND RELATED STATISTICS

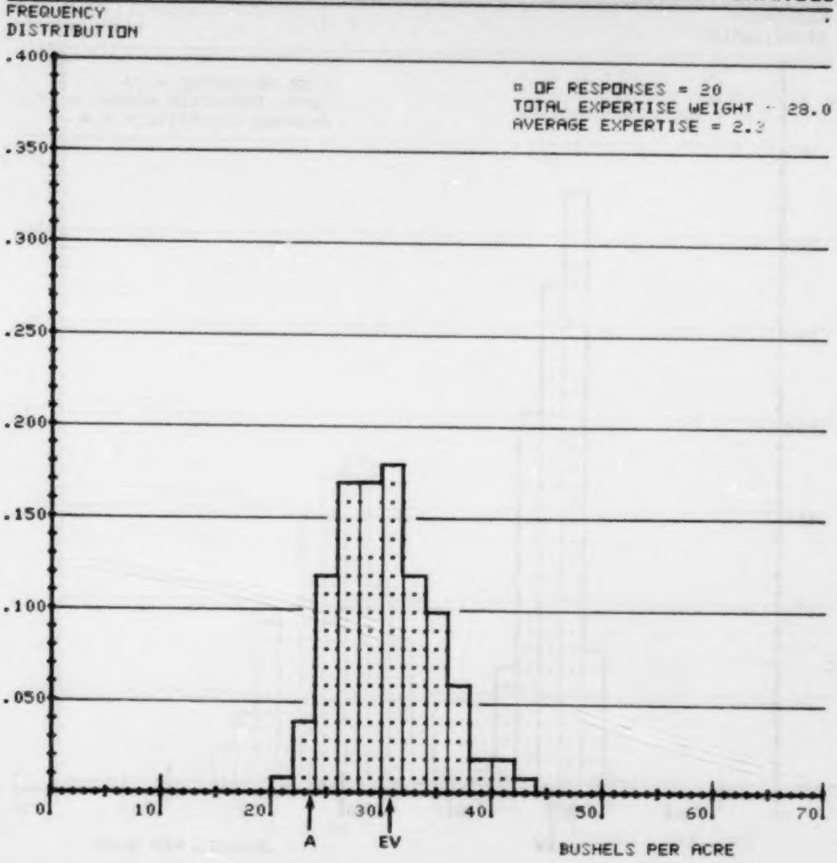
PROB	VAL	PROB	VAL	PROB	VAL	PROB	VAL
0	14.0	5	16.2	10	16.9	15	17.4
20	17.9	25	18.3	30	18.6	35	18.9
40	19.3	45	19.6	50	20.0	55	20.3
60	20.7	65	21.1	70	21.6	75	22.3
80	23.1	85	24.0	90	25.4	95	27.6
100	38.5						

VAL	PROB	VAL	PROB	VAL	PROB	VAL	PROB	VAL	PROB
2.	0.0	4.	0.0	6.	0.0	8.	0.0	10.	0.0
12.	0.0	14.	0.0	16.	4.1	18.	21.3	20.	50.5
22.	73.0	24.	85.1	26.	92.0	28.	95.5	30.	98.1
32.	99.1	34.	99.5	36.	99.7	38.	99.9	40.	100.0

EXPECTED VALUE = 20.64
STANDARD DEVIATION = 3.51
COEFFICIENT OF VARIABILITY = .1700
SKEWNESS = 1.25
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 16.5 BUS./ACRE (1.11 TONS/HA.)

Figure B-2.10

ARGENTINE WHEAT YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES

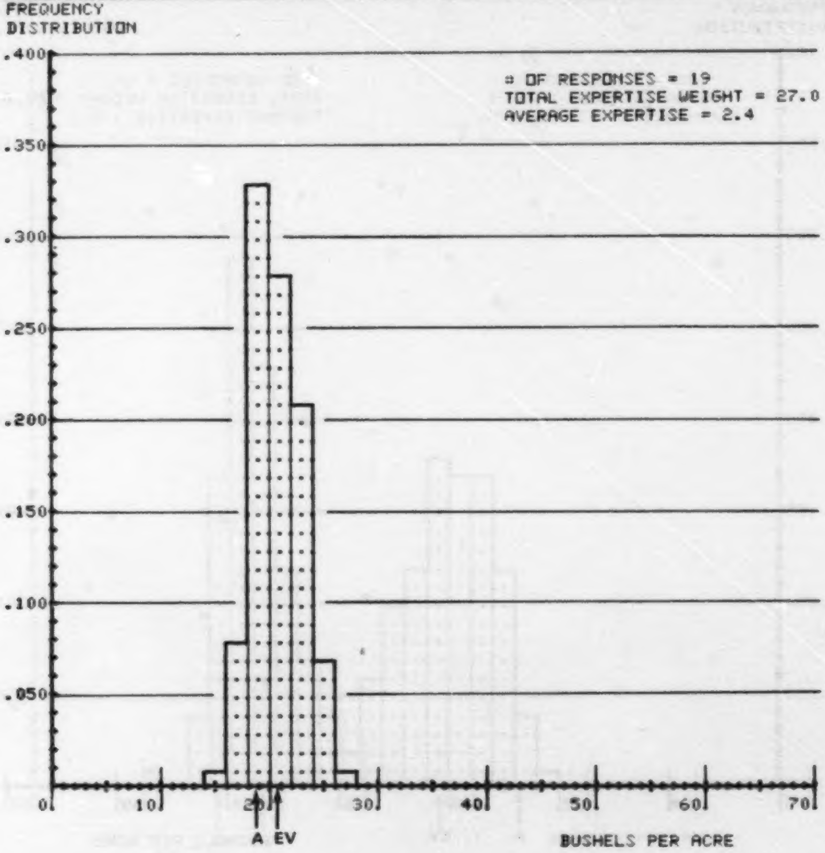


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

         PROB  VAL   PROB  VAL   PROB  VAL   PROB  VAL
            0  18.5     5  23.9    10  24.9    15  25.6
           20  26.3    25  26.9    30  27.5    35  28.1
           40  28.8    45  29.6    50  30.4    55  31.0
           60  31.5    65  32.0    70  32.7    75  33.6
           80  34.5    85  35.5    90  36.7    95  40.1
          100  59.7

          VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB
           2.   0.0   4.   0.0   6.   0.0   8.   0.0  10.   0.0
          12.   0.0  14.   0.0  16.   0.0  18.   0.0  20.   0.4
          22.   1.5  24.   5.3  26.  17.7  28.  34.3  30.  47.5
          32.  65.5  34.  77.3  36.  87.1  38.  92.7  40.  94.9
          42.  96.5  44.  97.2  46.  97.6  48.  98.1  50.  98.5
          52.  98.9  54.  99.4  56.  99.6  58.  99.9  60. 100.0
```

```
EXPECTED VALUE =  30.82
STANDARD DEVIATION =   5.54
COEFFICIENT OF VARIABILITY =  .1799
SKEWNESS =   1.41
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 23.3 BUS./ACRE (1.57 TONS/HA.)
```

Figure B-2.11

AUSTRALIAN WHEAT YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES

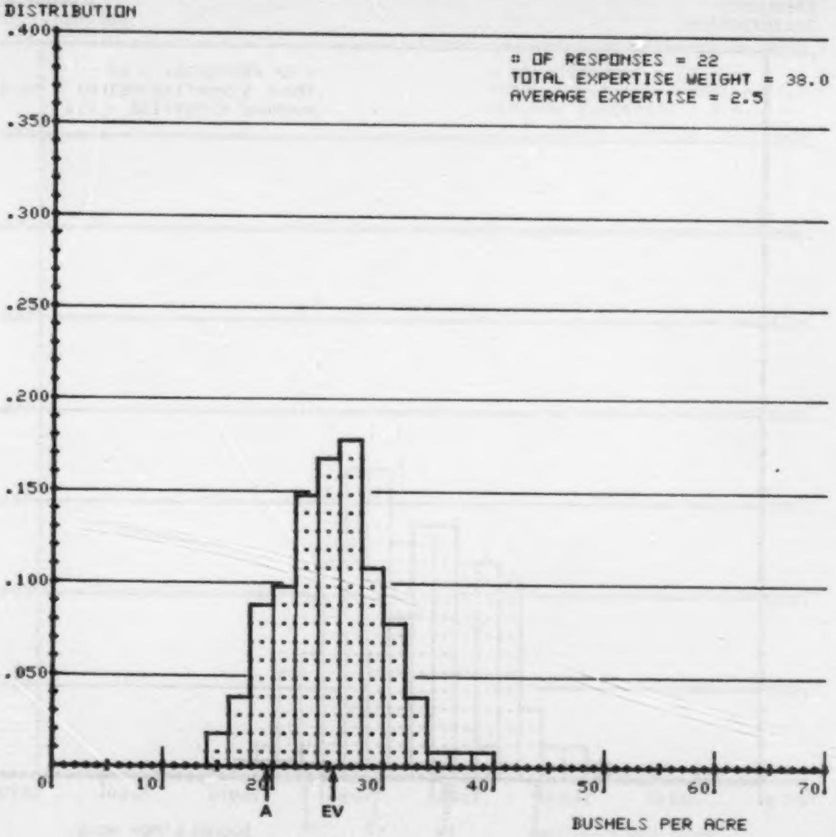


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

        PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL
           0  14.6    5  17.6   10  18.0   15  18.4
          20  18.8   25  19.0   30  19.2   35  19.5
          40  19.9   45  20.2   50  20.6   55  20.9
          60  21.2   65  21.6   70  22.0   75  22.3
          80  22.7   85  23.2   90  23.8   95  24.7
         100  31.3

         VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB
          2.   0.0  4.    0.0  6.    0.0  8.    0.0  10.   0.0
         12.   0.0  14.   0.0  16.   1.0  18.   9.3  20.  41.9
         22.  70.3  24.  91.4  26.  98.4  28.  99.5  30.  99.8
         32. 100.0
```

```
EXPECTED VALUE =  20.76
STANDARD DEVIATION =   2.30
COEFFICIENT OF VARIABILITY =  .1109
SKEWNESS =   0.52
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 18.7 BUS./ACRE (1.25 TONS/HA.)
```

Figure B-2.12

INDIAN WHEAT YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES

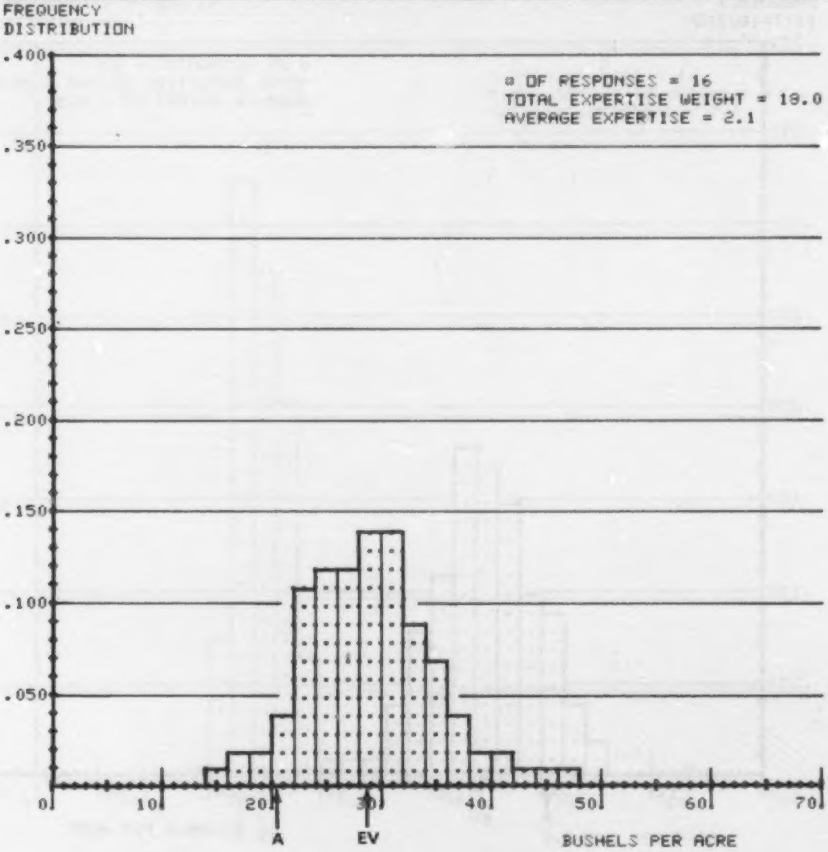


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

           PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL
              0  14.7    5  17.6   10  19.0   15  20.0
             20  21.2   25  22.1   30  22.8   35  23.5
             40  24.0   45  24.5   50  25.1   55  25.7
             60  26.4   65  26.9   70  27.5   75  28.0
             80  28.8   85  29.9   90  31.1   95  32.9
            100  42.5

            VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB
             2.   0.0   4.   0.0   6.   0.0   8.   0.0  10.   0.0
            12.   0.0  14.   0.0  16.   1.9  18.   6.0  20.  14.8
            22.  24.4  24.  39.9  26.  57.1  28.  74.7  30.  85.3
            32.  93.1  34.  96.6  36.  97.7  38.  98.6  40.  99.4
            42.  99.9  44. 100.0
```

```
EXPECTED VALUE =  25.21
STANDARD DEVIATION =    4.75
COEFFICIENT OF VARIABILITY =  .1883
SKEWNESS =   0.34
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 19.5 BUS./ACRE (1.31 TONS/HA.)
```

Figure B-2.13

PRC WINTER WHEAT YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES

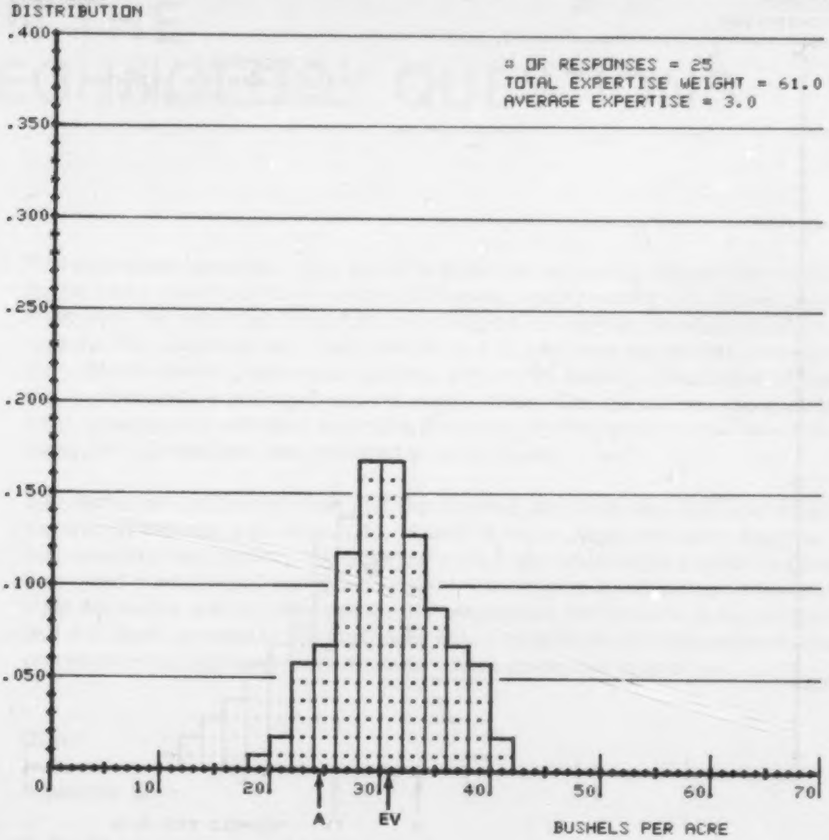


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

        PROB   VAL  PROB   VAL  PROB   VAL  PROB   VAL
           0  15.4     5  19.9    10  22.1    15  23.1
          20  23.9    25  24.6    30  25.5    35  26.3
          40  27.2    45  27.9    50  28.7    55  29.4
          60  30.2    65  31.0    70  31.6    75  32.3
          80  33.5    85  34.8    90  36.5    95  40.1
         100  48.0

         VAL  PROB   VAL  PROB   VAL  PROB   VAL  PROB   VAL  PROB
          2.   0.0    4.   0.0    6.   0.0    8.   0.0   10.   0.0
         12.   0.0   14.   0.0   16.   0.6   18.   2.8   20.   5.2
         22.   9.7   24.  20.9   26.  33.1   28.  45.4   30.  59.1
         32.  73.3   34.  82.0   36.  88.8   38.  92.5   40.  94.9
         42.  96.9   44.  98.3   46.  99.4   48. 100.0
```

```
EXPECTED VALUE =  28.96
STANDARD DEVIATION =    5.94
COEFFICIENT OF VARIABILITY =  .2052
SKEWNESS =    0.42
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 20.8 BUS./ACRE (1.40 TONS/HA.)
```

Figure B-2.14

U.S. WINTER WHEAT YIELDS, SELECTED STATES
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES

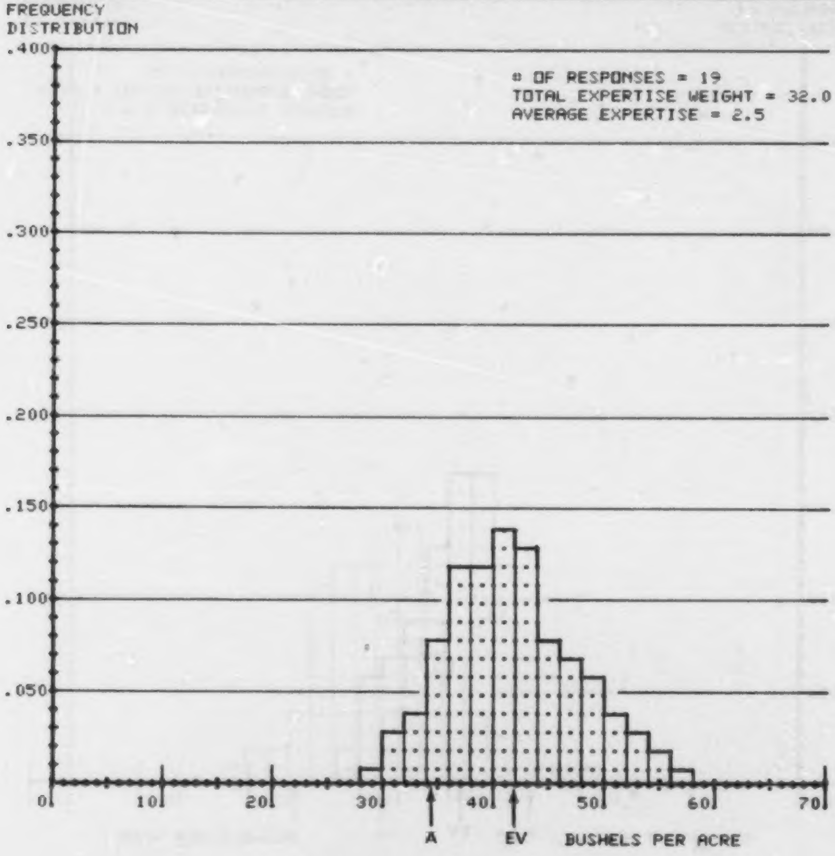


```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

       PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL
          0  18.8    5  22.7   10  24.3   15  25.7
         20  26.8   25  27.6   30  28.2   35  28.8
         40  29.4   45  30.0   50  30.5   55  31.1
         60  31.7   65  32.3   70  33.0   75  33.9
         80  35.0   85  36.1   90  37.5   95  39.1
        100  51.3

        VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB  VAL  PROB
         2.   0.0   4.   0.0   6.   0.0   8.   0.0  10.   0.0
        12.   0.0  14.   0.0  16.   0.0  18.   0.0  20.   0.6
        22.   3.1  24.   9.0  26.  16.0  28.  28.3  30.  45.4
        32.  62.3  34.  75.5  36.  84.7  38.  91.5  40.  97.3
        42.  99.3  44.  99.6  46.  99.7  48.  99.8  50.  99.9
        52. 100.0
```

```
EXPECTED VALUE =  30.76
STANDARD DEVIATION =   4.86
COEFFICIENT OF VARIABILITY =  .1581
SKEWNESS =   0.20
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 24.5 BUS./ACRE (1.65 TONS/HA.)
```

Figure B-2.15

USSR WINTER WHEAT YIELDS
PROJECTION OF YIELD IN THE YEAR 2000 DUE TO TECHNOLOGY CHANGES



```
CUMULATIVE PROBABILITY AND RELATED STATISTICS

            PROB   VAL  PROB   VAL  PROB   VAL  PROB   VAL
               0  28.9     5  32.5    10  34.7    15  35.8
              20  36.7    25  37.5    30  38.3    35  39.1
              40  39.9    45  40.7    50  41.4    55  42.1
              60  42.9    65  43.6    70  44.7    75  45.9
              80  47.3    85  48.8    90  50.5    95  53.1
             100  71.4

             VAL  PROB   VAL  PROB   VAL  PROB   VAL  PROB   VAL  PROB
              2.   0.0   4.    0.0   6.    0.0   8.    0.0  10.    0.0
             12.   0.0  14.    0.0  16.    0.0  18.    0.0  20.    0.0
             22.   0.0  24.    0.0  26.    0.0  28.    0.0  30.    1.3
             32.   4.1  34.    8.2  36.   16.0  38.   28.0  40.   40.5
             42.  54.1  44.   67.3  46.   75.6  48.   82.3  50.   88.8
             52.  93.0  54.   96.4  56.   98.0  58.   98.7  60.   99.0
             62.  99.2  64.   99.3  66.   99.5  68.   99.7  70.   99.9
             72. 100.0
```

```
EXPECTED VALUE =  42.04
STANDARD DEVIATION =   6.39
COEFFICIENT OF VARIABILITY =  .1519
SKEWNESS =   0.70
TOTAL PROBABILITY =1.000
AVERAGE 1972/76 YIELD IS 34.2 BUS./ACRE(2.30 TONS/HA.)
```

APPENDIX B-3

PANELISTS' COMMENTS ON THE TECHNOLOGY QUESTIONS

The agriculture panelists were asked to state the reasoning behind their responses to the Part I questions in the crop-yield survey (see Appendix A-1). These questions dealt with the potential effects of technological change in the absence of climatic change. The panelists also were invited to cite pertinent references. Almost all of the comments and citations are quoted, with minor editing, irrespective of whether the corresponding yield projections were usable. The quotations are grouped by crop, country, and self-rated expertise. Expertise scores, which range from 4 (Expert) down to 1 (Unfamiliar), are indicated in parentheses.

The reader should bear in mind that the remarks date from late 1977 and early 1978. Several comments, e.g., Nos. 3, 13, 16 and 19 under Argentine corn, apply to more than one crop and country. We have included a few observations made by panelists who rated themselves "Unfamiliar" with a country-crop combination, although their yield estimates are not reflected in the aggregated projections of Appendixes B-1 and B-2. Such comments are presented solely to indicate the respondents' thought processes when venturing guesses about crops outside their specialties.

CORN

Argentine Corn

1. Median increase in yield (10 percent) expected to be associated with increased use of fertilizer. Upper-limit estimate based on continuation of trend of the past 20 years. Lower limit based on stabilization of technology at 1980 level. My lower-limit trend, i.e., no change in technology, is based on the assessment that 1-in-10 chance will be somewhere between a small increase and a small decrease. (3)

2. Lower line—plenty of technology available if political, etc., factors are conducive to adopting technology. Middle line terminating at 70 bu/acre—essentially same reasoning. Upper line is probably conservative; it seems available technology could lead to even higher yields. (3)

3. The 50/50 path based on technology rate same as past rate. Considerable room for increased use of present technology. If no further increase, and if acreage expanded to more marginal areas, would get no increase in yields. Although trends are shown as straight lines, most likely they will follow more irregular paths (applies to all crops). (3) Reference: *Corn and Corn Development;* Monograph of Amer. Soc. Agronomy.

4. Yields are well below potential. Progress probably depends more on economics and politics than agronomy. (3)

5. Depends on the potential for irrigation. Variance in water could devastate in many years. Top line assumes they do better with insect control. Also more fertilizer could mean significant increase. (3)

6. The incomplete use of hybrid corn and slight use of fertilizer are likely to be overcome in next 20 years. This should produce at least a 50-percent increase in yields (assuming fertilizers are made available). Adoption will likely take at least 10 to 15 years to occur, so curves may be exponential, not linear. (3)

7. Argentina is now at about the same point technologically as the U.S. was in the 50s. Exact analogies cannot be made, but the only major difference is Argentina's common use of herbicides. Mechanization is, for the most part, late 40s–early 50s. Technical improvement in planting techniques *could* be made quickly. Major technology advances (more fertilizer use, more-efficient mechanization) depend mainly on political and social factors. The top line is similar to U.S. trend (ca. 90 bu/acre in 2000) and is based on rapid solution of political, social and economic problems, as well as establishment of a better agricultural education infrastructure. (This may be *too* optimistic.) The bottom line is based on using the current level of technology. Since little fertilizer is used now, the energy problem should not influence them much. The 50/50 line is simply trend extrapolation. (3)

8. I feel that Argentina has been slow to adopt available and transferable technology for corn production, but will do this in the next decade. The long corn-growing season in Argentina should allow the multiple-ear hybrids, thus reducing drought risks. (3)

9. Even chance—no breakthroughs, rate same as past. Upper limit—possible breakthrough. Lower limit—energy limited. (3)

10. I have based my estimates on the idea that Argentine production is limited by fertilizer availability, an economic problem. Once fertilizer begins to be used, I believe a rapid increase in production will occur but proceed at the time rate of increase that occurred in the U.S. from the 1950s to the 1970s. My 50/50 trend line is based on that assumption. (3)

11. Corn yield increase should have a different trend than wheat because the technology of corn production in North America has not been fully implemented in Argentina as yet. This should be gradually applied to about 1980, then as a greater percentage of farmers apply the new technology (hybrids and nitrogen fertilizer), the yield increase will be greater in the 1980-to-1990 period and then really accelerate in the 1990-to-2000 decade. It should easily hit a 70-bu/acre average by the year 2000! (3)

12. Argentine corn yields are largely limited by nitrogen fertilizer, and climatic-edaphic potential exists for increasing yields to 55 bu/acre in 25 years. The weather-induced variability is 14 percent, considerably larger than that for the U.S. corn belt, 10 percent. (3)

13. Optimistic forecast assumes rapid utilization of U.S. technology is possible and is executed. The 50/50 forecast is an extrapolation of data by eyeball. Pessimistic forecast is approximately current 10-percent line and assumes no further technological advancement. These assumptions are repeated in each subsequent analysis. (2)

14. Low curve based on hypothesis that there will be moderate yield increases due to improved mechanization and hybrids. Median curve based on hypothesis that fertilizer use will become more widespread plus some increase from hybrids. High curve based on hypothesis of rapid increase of fertilizer and some gains due to new hybrids—increase would be similar in percent to U.S. gains 1950-1965. Ultimate 2000

AD yield levels: (a) will remain as variable due to climate; (b) average yield should rise significantly; but (c) will not reach U.S. 1975 yield levels due to poorer soils and difficulties of getting the diverse growing locations all to be near optimum production. (2)

15. Argentine corn is grown in an area dependent upon natural fertility of the soil. The curve drawn for an even chance assumes that technology will allow for management of the soil to maintain fertility through crop rotation, etc. I would expect a rather large interval between 1/10 chance of less yield and 1/10 chance of higher yield because of the frequent occurrence of drought years; this would negate the effect of fertility. (2)

16. Argentina is likely to follow the lead of Brazil in developing improved agricultural technology, but her political problems may constrain the rate of development to a somewhat slower one than in Brazil. There is so much yield improvement for Argentina to get out of more fertilizer that I drew the "high" trend line with a substantially increased slope.

Every trend line for every crop-nation combination is straight from point A until the year 2000. This straight-line "model" is not intended to suggest that agricultural technology is discovered smoothly, because there indeed are breakthroughs. The straightness of the lines is the result of the slow, gradual process of transferring new technology to millions of farmers, who adopt new technology at different rates.

Every "low" trend line is given a slight positive slope to express my belief that there probably won't be a technological catastrophe that ruins crop yields, even if the weather is favorable. This low line would only happen if there were no major advances in technology over the next quarter century and if the only progress were slow, incremental fine-tuning of farming practices. (2)

17. As U.S. technology is adopted and more adapted hybrids are developed more uniformly, increasing yields can be expected. The climate seems favorable for higher yields than are presently obtained. (2)

18. We have had the best results with yield models that have a flat technology trend line since the early 1970s. (2)

19. Technology, particularly fertilizer and machinery, will become increasingly expensive. Given no climate change, then everything hinges upon demand and price of inputs. Without a serious decrease in yield or major change in the agricultural price structure, I believe that in the less developed countries technology will have to lag appreciably. This will be true for most countries, but most particularly the less developed countries. This may be less true for Russia and China, which will probably devote much attention to agricultural production. (2)

20. Path 1 (lower)—very unlikely because fertilizer use is on the increase. Path 2—a 25-percent increase is likely because of improved technology. Path 3 (upper)—a 50-percent increase is unlikely because of high cost of fertilizer and competition in the world corn market. (2)

21. Yields increased by increased use of hybrids and fertilizer, and better mechanization. These increasing factors may be diminished by moving production into marginal areas. (2)

22. The trend paths are a guess. I believe the technology in use has a long way to go to catch up with present crop-production management knowledge. I don't think the present trend will continue for the entire period. There will be some temporary setbacks. (1)

TECHNOLOGY COMMENTS

U.S. Corn

1. Expect an increase in yield per unit land area through 1980 because of the retirement of some marginal production land. Thereafter, the upper path reflects the trend of past few years. The lower path reflects no change in technology after 1980. (4)

2. Cultivar selection to overcome problems has just begun. Should lead to yield increases over time. Static yield in last few years mostly climate related. (4)

3. Evidence indicates technology trend is flattening out (50/50 line). With low prices, there could even be a decreasing trend. As acreage is reduced (and prices go up), increased yields are expected on better land. (4)

4. Corn yields, especially in the corn belt states, are nearly at a peak in varietal yields and technology. (4)

5. Upper line assumes no fertilizer-cost or pesticide-use problems. Lower line assumes longer duration of use problems. Median line to 105 bu/acre assumes time will be required for safe pesticides. (4)

6. Not much chance for greater than 10-percent technology developments in next 20 years. (4)

7. Path 1 (lower) shows increase to 90 bu/acre, which is near but above present yields. An increase to 100 is possible since yields have already reached 97 in a good year. An increase to 110 is possible given adequate supply of nitrogen. (4)

8. One must consider that the maximum yield of corn in the U.S. has continued to increase each year. In 1977 the record goes to Michigan with over 350 bu/acre on a measured 1.9 acres. The rest of the field averaged about 280 bu/acre. With the same climate and soil resources, the surrounding production was less. The difference was application of current technology. Thus, I feel the average must move upward unless technology falls back. Because of EPA, OSHA, IRS, etc., this is possible. For example, rapid vigorous enforcement by EPA of section 208 will eliminate most agricultural production of row crops in the states on the southern and eastern edges of the U.S. corn belt. Because of sloping land and rainfall intensity, erosion potential cannot be reduced enough without a technological breakthrough. These are less predictable than next season's weather. Another factor is energy, about which there is too little space to say much. Energy problems might force the use of technology inappropriate to a goal of maintaining increasing production. (4)

9. Top line assumes continued expansion of corn as an irrigated crop in the western corn belt and further expansion, under irrigation, in parts of the Great Plains States, as well as continued economically justified supplies of nitrogen and/or N-fixing microbes compatible with typical grasses. Also assumes that hybrids more resistant to drought will be developed. Midline to 105 bu/acre assumes continued progress in breeding corn hybrids resistant to diseases, insects and moderate environmental stress. Bottom line assumes restricted use of nitrogen in corn production necessitated by environmental considerations, high prices, or both. (4)

10. I expect a modest increase in U.S. corn yields at about 1 percent per year over the next 25 years. This improvement could be as much as 2 percent per year. On the other hand, a cooler and drier climate could push the U.S. corn belt south and east to less desirable agricultural lands, thus causing the yields to remain near their current levels. (4)

11. Even chance—no breakthroughs, rate same as past. Upper limit—possible breakthrough. Lower limit—energy limited. (4)

12. Many papers have shown that drought is cyclical in nature. Although cause and effect are not understood, I have assumed an approximately 22-year cycle. Duration of each drought period is also highly variable. I have assumed short duration for the high-yield trend and long duration for the low-yield path. I also assumed that water will remain a very limiting factor but that chemicals will not. I do not think that we have the water resources to even out the drought effects even though technology for irrigation is well understood and valuable now. The overall area of influence is also highly variable and probably the eastern states will be wet while the western states are dry. (4)

13. Experimental plot yields of the best hybrids are now over 150 bu/acre when weather conditions are near "optimum." In some cases, county yields have now reached the average of experimental plot yields. Therefore, advanced technology of hybrid development, more-efficient use of water, etc., and wider acceptance of this technology by producers should boost the yields to 150 bu/acre average by the year 2000 with the trend as shown. A major breakthrough in germplasm might boost this closer to 170 bu/acre. (4)

14. U.S. corn yields are reaching an apparent ceiling of about 95 bu/acre. The weather-induced variability is likely to be greater than the 10 percent which was calculated for the previous 27-year period. (4)

15. Since 1950, U.S. corn yields have increased quickly because of increased fertilizer and hybrid breeding. Although no other great change in technology can now be seen, there is enough of a chance for me to put the high-trend line slightly steeper than the slope between 1957 and 1969. (3)

16. Median path: corn yields will continue to increase to about 130 bu/acre as new technology is adopted more thoroughly by growers. New hybrids and technology will also result in higher potential yields. Lower yields in the frontier areas will be offset by increases in traditional corn-growing regions. (3)

17. U.S. corn yields have exhibited a leveling-off similar to that for wheat and soybeans. See discussion for U.S. winter wheat (Comment No. 7). (3)

18. As I understand it, experimental plots can yield from 130 to over 300 bu/acre. I can only guess how much of this will come to the farmer by 2000. Improved drainage will help in much of the corn belt. (2)

19. Through further increase in crop engineering and hybrid development, yield will increase through the mid-1980s, then level off due to normal weather and localized poor growing conditions. (2)

20. Prospects for increasing yield—new varieties. Prospects for decreasing yield—reduced fertility levels resulting from fertilizer shortage, reduced fertility due to soil losses from erosion. Prospects for maintaining yield—new minimum tillage machinery and practices which can offset some of decreasing factors. (2)

RICE

Indian Rice

1. The median path (continuous line) has been drawn taking into consideration the rice production of 1951 to 1976 in India. In view of the lack of any breakthrough in the production of this cereal, a general trend curve was fitted without any split in the period. The dotted lines are the fiducial limits at 90 percent. (Expertise = 4, assigned by project staff)

2. I feel that it is possible to double the Indian rice yields. People and their governments do what they *must* do—and India must increase its yield—but will this happen? A main limiting factor in Indian agriculture is the human resource. I feel that their current trend in yield improvement will persist at about 2 percent per year, but could fall to 1 percent per year. (3)

3. Rice yields in India are limited largely by nitrogen fertilizer, and there is ample room for a steady yield increase if fertilizer is available. The weather-induced yield variability for Indian rice is quite low, 7 percent, compared to most crops. (3)

4. Continuing improvement of varieties, increased application of nitrogen fertilizer, and more-extensive irrigation of rice should cause a steady, but not dramatic, rise in Indian rice yields. (2)

5. Yields are relatively low and could be greatly improved with nitrogen fertilizer. (2)

6. With more-universal irrigation and fertilizer use, general production would increase for next 20 years. Energy considerations might cause low line to prevail. (2)

7. India, in many respects, is similar to China—overpopulated with favorable climate and soils for rice production (see PRC rice, Comment No. 1). If India can dramatically improve its rice technology in the next 20 years, a steep, rising technical trend is possible. (2)

8. I am not qualified to answer. See: Mallik, A.K. The Climatology of the Crop Seasons of India—1. Rice; *Indian Journal of Meteorology and Geophysics,* Vol. 151, 556-563. (1)

9. Upper path is based largely on past trend, which shows limited variability. The 50/50 path is at a lower rate. The lower path indicates a stagnation unless better varieties, etc., come along. Much is already irrigated. (1)

10. Path 1 (lower) indicates that yields will not decline but should improve some. Path 2 indicates less increase per year to 2000 than from 1950 to 1975. Path 3 (upper) indicates trend extrapolated from 1950 to 1975 (1)

11. Even chance—no breakthroughs, rate same as past. Upper limit—possible breakthrough. Lower limit—energy limited. A real question about energy here. (1)

12. I used linear projections of the peak yields for the high-yield trend line, of the mean for the average-yield trend line, and of the minimum yields for the low trend line. (1)

PRC Rice

1. China, under the new leadership, has determined to modernize her industry and agriculture. The National Conference on Agriculture, held early in 1977, drew up an

agricultural mechanization plan. With a population of nearly 900 million, China will have no problem of food overproduction in the foreseeable future. Natural environmental factors such as geography, soils and climate are no less favorable for rice production in China than in Japan. If by the year 2000 China can achieve the present Japanese level of technology, then China should at that time have the present rice yields of Japan, or roughly 5800 kg/ha. (3)

2. The even-chance line for PRC rice yields is drawn slightly more optimistic than the trend since 1967 because the Chinese will soon make more use of our new technology in addition to their own. The PRC is slowly but surely opening its doors to the Western world and this process will allow her to make more productive use of the new technology coming out of places like the International Rice Research Institute. In the case of PRC rice, and somewhat less for Indian rice, the actual yields will more closely follow a straight trend line than for other crops (see Argentine corn, Comment No. 16). This smaller variability around the trend line is because irrigation effectively dampens out the yield changes caused by precipitation variability. (2)

3. New varieties have given a recent kick to yields. More fertilizer would help since yields are still well below Japan's. (2)

4. Fertilizer and management technology could increase the trend line for 20 years (upper path). Better mechanization could help but may not be adopted (center path). (2)

5. I feel that China will develop the human resources in agriculture necessary to feed its people. Also, it is likely to be technically possible to produce 5 metric tons per hectare as a national average in China by year 2000. If climate becomes more hazardous, PRC rice production could remain near 3.0 to 3.5 metric tons per hectare. I estimate that the increase in PRC rice production will remain near 2 percent per year. (2)

6. There is ample room for increased yields of rice in China; the major limitation is nitrogen fertilizer. The overall weather-induced yield variability for rice in China is among the lowest for all crops (5 percent); however, the yield statistics for China are rather poor and actual yield variability likely is somewhat higher. With a lowering in temperature of more than 6 °C, a reduction in the area planted to rice along the northen fringe of the rice belt in China would occur. (2)

7. Upper limit a continuation of trend. Mean value based on approximately one half of the increases by extending existing trend. Lower limit—no change in technology. Very low confidence in this estimate. (1)

8. Probably have reached near-maximum potential. New varieties may produce small new-term increase in yield. (1)

9. Since most of the rice is irrigated, climate has only a temperature effect on yield. Yield increases are then dependent on varietal improvement, fertilizer and pesticides. (1)

SOYBEANS

Brazilian Soybeans

1. Trends of the past 10 years should continue through 1980. After 1980 the technologies should be "caught up" in Brazil and a lower rate of change realized. (4)

2. Soybean acreage has been increasing in recent years, and this will continue in the years ahead, in regions of better climatic conditions for this crop (Parana, Sao Paulo, Matto Grosso, Goias and Minas Gerais States). Better technology is being developed and introduced to farmers in Brazil. (4)

3. Guess only! (4)

4. Soybean yields will increase due to improved varieties and improved technology in the double-cropping system. I expect yields to remain rather constant with minor year-to-year variation. (3) Reference: Sediyama, G. Simulation of Subtropical Environmental Parameters for Modeling Irrigation Requirements, Machinery Timeliness Factors and Production Response of Soybeans; Ph.D. dissertation, University of California-Davis, 1977.

5. Brazil appears to have a very favorable climate for soybeans, and the recent rapid yield increase will continue as widespread use of modern technology is more uniformly adopted. Subsequent yield increases will be slower and will probably be of a magnitude similar to that in the U.S. (see U.S. soybeans, Comment No. 2). (3)

6. U.S. technology largely adapted already. Expect little technology increase. Acreage expansion into less desirable areas. (3) Reference: Thompson, L. M. Weather and Technology in the Production of Soybeans; Iowa State University, CAED Report No. 17.

7. Large recent yield increase is due to efforts of better farmers. Progress will slow as crop is extended to poorer land and farmers. (3)

8. Top line assumes new varieties incorporating reduced photo-respiratory losses and higher light saturation levels for photosynthetic response through bred-in canopy architectural changes for soybeans adapted to the Brazilian climate. There is a good opportunity to increase soybean production in subtropical temperatures by means of supplemental irrigation. Midline to 39 bu/acre considers Brazil's generally improving agriculture, investments in training extension and research workers; bean yields are considerably below those in the U.S. and should improve as skill in farming improves. Bottomline assumes little improvement in technology of soybean production or in varieties. Energy shortages in the future will have relatively smaller effects on legumes than on other crops. (3)

9. After adoption of proper technology, the Brazilian soybean yield is likely to increase by about 3 percent. If diseases are controlled it could be 5 percent, but if diseases are not controlled and increasingly marginal lands are brought into production, the yield could drop. (3)

10. Even chance—no breakthroughs, rate same as past. Upper limit—possible breakthrough. Lower limit—energy limited. Assume fairly rapid transfer of technology from the U.S. (3)

11. Brazilian soybean yields have climbed rapidly for the past 12 years, and now are similar to those for the U.S. A leveling-off is now likely. The weather-induced yield variability in Brazilian soybean yields is considerably larger than that for the U.S. (3)

12. This is the only foreign soybean combination to be treated in this study. Although U.S. soybean yields have been increasing slowly in comparison with U.S. wheat and corn yields, the growth of soybean yields and production in Brazil has been explosive in recent years. I expect Brazilian soybean yields to increase rather rapidly until the year 2000 because of an aggressive policy there in support of the

new soybean industry. I don't expect the yield to increase as rapidly as the last few years because it will take a breakthrough in nitrogen fixation technology to support such a high rate of growth. This breakthrough will not come easily nor before 1990 on farmers' fields. (2)

13. As more land comes into production, yield increases will be harder to realize than from 1965 to present. (2)

14. Irrigation would help yields. New varieties would not help much very soon. They use our better adapted varieties now. (2)

15. Additional lands brought into soybeans will be poorer, making it difficult to drive bean yields (national average) up very fast. (2)

16. Path 1 (lower)—yields are likely to improve although it is possible that expanding acreage might cause a level trend. Path 2—a trend to 30 bu/acre is the more reasonable expectation—about where the U.S. is now. Path 3 (upper)—possible but unlikely (2)

17. Soybean yields are already high relative to U.S. standards. Brazil is doing a good job with soybeans, and yield-trend lines were drawn to parallel those estimated for the U.S. (see U.S. soybeans, Comment No. 19). (2)

18. Will require considerable additional energy to increase yields. (1)

U.S. Soybeans

1. This reporter has a bias that indicates an expectation for increased productivity of soybeans over the next two and a half decades to about 33 bu/acre. This increase will occur because of genetic improvements and management systems. The lower limit is based on no change in technology. (4)

2. Soybeans will experience a gradual increase, primarily due to development of superior varieties and improved weed control. (4)

3. Expect some increase in technology (50/50), but major increases (1/10) not likely, nor are stable yields. (4) Reference: see Brazilian soybeans, Comment No. 6.

4. Nothing in the offing to change yields. Economic factors that would bring in many new growers could lower average. (4)

5. A sizeable technology breakthrough can be expected. (4)

6. Path 1 (lower) is drawn to indicate that some yield increase is highly probable. Path 2 shows an increase of 5 bushels in 20 years or about 0.25 bushel per year. Yields have been increasing at about 1/3 bushel per year. Path 3 (upper) shows the same trend as the past 30 years. (4)

7. Upper line assumes improved varieties, especially through suppression of the photorespiratory mechanisms and development of canopy architectures to improve light penetration. Further assumes expansion of U.S. soybean production westward under supplemental or full irrigation. Midline to 33 bu/acre assumes costs of production inputs (energy, fertilizer, machinery) reduce impacts of improved varieties. Lower line assumes costs of production lead to less intensive modes of production of soybeans (i.e., less weed control, lower fertility levels, etc.). (4)

8. I expect a steady, current, yield-trend improvement in soybeans. Much of the increase is likely to come as improved cultural practices have their effects. (4)

9. Even chance—no breakthroughs, rate same as past. Upper limit—possible breakthroughs. Lower limit—energy limited. (4)

10. Increase in soybean yields will continue to be less spectacular than corn. Averages by the year 2000 will still be below 40 bu/acre. Variability from year to year may be greater, as has occurred during the last 5 years. (4)

11. The weather-induced yield variability for soybeans is among the lowest for all crops. For the U.S. it is 6 percent for the 27-year period. (4)

12. Soybean yields have been increasing slowly, and it does not appear that new varieties will greatly increase yields by the end of the century. (3)

13. The odds are that we can sustain the same increase as accomplished during the 1960s with modest improvement in practices. If we get a breakthrough in our understanding and control of nitrogen fixation, then we may be able to achieve the high line. (3)

14. Improvements in genetics and mechanical harvesting are possible. (3)

15. (1/10) higher—genetic advances. (1/10) lower—governmental interference, price control, EPA enforcement of section 208. (3)

16. U.S. soybean yields have exhibited a leveling-off similar to that for wheat and corn (see U.S. winter wheat, Comment No. 7). (3)

17. Response to fertilizers is so small that the trend will always be modest. New varieties and weed control will constitute major impetus for future production increases. (2)

18. Concerns are identical to those expressed for U.S. corn (Comment No. 20). (2)

19. I have assumed that major drought effects will be averaged out for the entire U.S. soybean yields since most droughts affect only one fourth or less of the total U.S. area at any one time. I assume fertilizers and other chemicals will not be limiting factors. (2)

SPRING WHEAT

Canadian Wheat

1. Lower (10-percent chance) trend line: This is very subjective but I've suggested a leveling-off at "A," i.e., about 26 bu/acre, which was the 1972-76 average. There are several arguments why such a leveling-off is possible. Further technological advances might improve the yield per unit of labor or unit of capital input (including energy), or they might simply help to avoid disasters such as the 1954 Canadian prairie rust epidemic which cut Canada's wheat yield about in half, without increasing the yield per unit of land area. Also, the 1972-76 period lacked such dry years in western Canada as the late 50s and 1961, so 1972-76 weather may have averaged better than normal. In analyzing Canadian prairie crop-district yields for trend I found, for 1963-72, trends of +0.1 bu/acre per year on the brown soils, −0.1 bu/acre per year on the dark brown, and +0.5 bu/acre per year on the black, dark grey, etc. From all this I conclude that a leveling-off at 1972-76 levels, or even a decline, is possible

but not too probable, and I suggest that a horizontal line from point A is a reasonable approximation of a limit below which there would be only 1 chance in 10 that the actual yield trend from now to the year 2000 would fall.

Middle (50-percent) trend line: In the absence of any basis for predicting future technological breakthroughs, I will base my projection on examination of historical data. Because of moisture limitations in the prairie provinces, where 95 percent or more of Canada's wheat is produced, and because modern technology is already being applied there, I would expect that Canada's wheat yields per acre would increase only quite slowly. A reasonable theoretical approach to projecting yields would be to identify, in a historical yield series, the part of the variability that can be attributed to weather variability, and then to determine what the trend would be with these weather effects removed and extrapolate that trend for projection purposes. The importance of trying to remove the weather effects can be seen from the fact that 1961-72 wheat yields for Canadian prairie crop districts appeared to increase about 1 bu/acre per year, when analyzed in relation to time alone, but when terms were included to try to account for weather effects, the remaining trend appeared to be only about 0.5 bu/acre per year. Even this lower value I think still reflected a considerable effect relating to the fact that the first year of the period, 1961, was a very severe drought year in western Canada, so that any trend starting with that year appears quite positive. Indeed, the weighted average of the trends on different soils for 1963-72 mentioned above was 0.23 bu/acre per year.

Another approach is to assume that weather-induced fluctuations in yields will even out if a long enough period is analyzed, thus avoiding the problem of having to separate weather effects from other trend effects. I examined 1885-1977 Canadian prairie wheat yields and found that, apart from the exreme year-to-year fluctuations, there was a tendency for yields first to decrease in earlier years, and then to increase in recent years. A parabola, concave upward, could be fitted and used to represent this trend, but I would hesitate to extrapolate into the future along it because this would give a yield projection that accelerates upward, which I'm not sure is justified. A higher power curve might be used to overcome this, but the danger there is that with more terms the equation is simply better fitted to past weather fluctuations and therefore not dependable for projection.

I therefore fitted a simple linear regression line to the Canadian prairie aggregate wheat yields for 1923 to 1977. I used 1923 to start because that was the year of the lowest point on the fitted parabola for 1885 to 1977, and because I wanted to avoid having the poor conditions of the 30s give my straight line too steep a trend (as 1961 had given too steep a trend in the 1961-72 study). The resulting equation for estimating Canadian prairie wheat yield projections in bu/acre is

$$Y = 12.6332 + 0.225306 X,$$

where $X = 1$ for 1923, 2 for 1924, etc. The slope, 0.23 bu/acre per year, turned out to be the same as the trend in the 1963-72 crop-district analysis obtained after removing weather effects as discussed previously. Taking the 1972-76 average for all Canada, 26.04 bu/acre (point A) plotted at 1974 as the starting point, the 1980 value was computed as 26.04 + (6)(0.225306), and the 1990 and 2000 values were computed similarly using 16 and 26 times the slope. The three resulting values—27.39 for 1980, 29.64 for 1990 and 31.90 for 2000—were then plotted and joined to "A" at 1974 in a straight line for my middle trend line, i.e., the line above and below which I suggest there is an equal chance that the actual trend to 2000 would fall.

As I do not have a basis for predicting a technological breakthrough with respect to wheat yield, and I think the likelihood of converting substantial acreages to irrigated wheat would be much less than 1 in 10, I find it hard to suggest anything in the way of an upper 10-percent line for wheat yield. Working in terms of total production, however, I think a logical consideration would be the possibility that if demand greatly increased, most of the acreage that is in summerfallow under present management practices would be used for wheat. The mean Canadian wheat acreage for 1972–76 was 23,662,860 acres, so multiplying this by the bu/acre values above results in a graph of production in bushels, assuming constant acreage at this level.

The total Canadian prairie summerfallow acreage in any year is usually somewhat larger than Canada's total wheat acreage. This summerfallow is typically in 2-year wheat/fallow rotations, or it may be barley/fallow or some other combination, and often the cereal is grown several years in a row. Wheat seeded on stubble, i.e., after wheat or another cereal, usually yields about 80 percent as much as the overall average for prairie wheat seeded on fallow and stubble. A lot of the wheat seeded on stubble would probably be on fields where the farmers considered the moisture situation was not too limiting. If wheat was planted every year on stubble, thereby doubling Canada's wheat acreage and practically eliminating summerfallow, the yields would probably be considerably lower than 80 percent of the expected yields with the present mixture of fallow and stubble seeding, but as long as the percentage was greater than 50 percent, total wheat production would be higher because the acreage would be doubled.

I have arbitrarily assumed that wheat yields with this doubling of wheat acreage and elimination of most of the summerfallow would be 67 percent of the yields to be expected with a continuation of present rotations, and that there might be a gradual conversion to this system, to be completed by the year 2000. Then, taking the value of 31.9 for the year 2000 and multiplying by (.67)(2)(23,662,860), I get an estimated production for the upper line for that year of 1,011,492,614 bushels of wheat. For comparison, the projection from the middle line is (31.9)(23,662,860) = 745,845,234 bushels.

To obtain the upper 10-percent production line, i.e., the line above which I suggest there would be less than 1 chance in 10 of the actual production trend line from now to 2000 falling, I joined the 1.0115-billion bushel point for the year 2000 calculated as described above to "A," which is (26.04)(23,662,860) = 616,180,874 bushels production plotted on 1974. This assumes a gradual conversion to eliminate most summerfallow by the year 2000, after which production would be expected to become more or less parallel to the 50-percent trend line, i.e., the upper line and middle line would become parallel.

Of the many possible pitfalls to such computations, perhaps the most obvious one here is that commercial wheat yields under conditions of a crop every year might be smaller than I have suggested. They might, for example, be so small that total production would be no greater than would total production with a crop every other year. For such reasons, I would suggest the chances of production trends to the year 2000 being above my upper trend line would not be more than 1 in 10 even if I thought conversion to the one-crop-per-year system was very likely. (4)

2. The main source of higher yields is assumed to be varietal improvement. I project 7.5-percent, 20-percent and 40-percent increases by the year 2000 with respective probabilities of 0.1, 0.5 and 0.9 of lesser increases. Base yield is 26.0 bu/acre. (4) References: see U.S. spring wheat, Comment No. 4.

3. Canadian wheat yields have reached a level quite close to that for U.S. spring wheat yields (in an adjacent region). Therefore, it should be expected that future Canadian wheat yield trends should be similar to those for U.S. spring wheat. (4) (*Editor's note:* This panelist's only remark on U.S. spring wheat was a reference to his statement about U.S. winter wheat, Comment No. 7.)

4. The main limiting factor in Canadian wheat production is climate—both precipitation and temperature. Therefore, adoption of technology is likely to bring about a limited yield increase of 3 percent or less per year. (4)

5. Canadian spring wheat yields average more than U.S. yields, and I expect them to increase gradually over the next 23 years due to increases in technology and improvement in varieties. There are numerous research projects under way on wheat response to the environment and I expect these to be realized in the form of yields. (3) Reference: Walker, G. K., Development of a Wheat Model for Land Evaluation; M.S. thesis, University of Saskatchewan, 1977.

6. Canadian wheat yields will continue to rise although, as in the case of Australia, they will continue to be erratic because of moisture deficits. Less emphasis on high quality, expanding winter wheat acreage, and less summerfallow will contribute to the increased production. (3)

7. With moisture the chief factor, there isn't much hope of doing more than continuing the present trend for a time. (3)

8. Present yields reflect high technology, and the potential for improvement is not great. (3)

9. It is possible but unlikely that yields would not increase (lower path). The increase in yield from technology has been small and will likely continue small (middle path). A trend to above the best yield so far would be unlikely (upper path). (3)

10. Upper path assumes continuing advance of winter wheat in southern Canada and expansion of short-season varieties into black-land soils. Canada's research establishment is excellent and hence varieties and management methods should continue to improve productivity of wheat farmers. Midline represents a modest improvement of yields achieved primarily through plant breeding, but limited by costs of energy (machinery and fertilizers, especially nitrogen). Lower path assumes severe restriction in nitrogen availability or excessive costs of same, making applications uneconomic. Also assumes that expansion of production into marginal climatic regions is unsuccessful. (3)

11. Wheat yields in western Canada will increase as the use of N(– P) fertilizer increases and new strong-straw varieties are developed. Increases will be greatest to the 1980s and then the rate of increase will slow down so that the average yields are not too likely to be higher than 40 bu/acre by 1990. As new lands are brought into production, which is likely to occur at an accelerating rate in the 1990-to-2000 decade when new short-season varieties should be available, the increase in average yields will not be as great. (3)

12. Severe climate limitations, both moisture and temperature, limit wheat yields in Canada; there is little room for improvement in yields. The weather-induced yield variability for Canadian wheat is among the highest for all crops, over 18 percent. (3)

13. The rate of increase through 1980 is based on the assumption that wheat acreage will decrease so the less productive lands will be retired from production. Slower growth rates should prevail after 1980. (2)

14. Continued use of modern farming techniques will undoubtedly keep Canada on the forefront of technology. Only economic conditions would prevent them from staying abreast with modern technology. It is therefore quite difficult to assess their future yields because they depend not on catching up to the leaders, but only on what technology may come on stream. (2)

15. Canadian wheat yield should progress similarly to U.S. wheat yield in that they both feed off common technology. There is some evidence that U.S. wheat yield has somewhat "plateaued" from its previous steady rise. The contribution of weather to the observed "plateauing," compared to the contribution of technology, is unknown (see U.S. spring wheat, Comment No. 16). (2)

16. Water limits yields in many areas to a large degree. (2)

17. Expect little change in present yield level, one way or the other. With low prices, yields may decrease some. With high prices, yields would increase some due to increased use of technology. (2)

18. Very little technological improvement can be expected because all the best land has been brought into production and opportunities for breakthroughs are very slight. (2)

19. Increase from new varieties only. Fertilizer, herbicides and additional machinery will be energy limited. New acreage unlikely. (2)

20. Canadian wheat-yield trend lines were drawn more or less parallel with those for U.S. spring wheat. My impression is that drought is not so predictable as in the U.S. plains, so I have not attempted to indicate any drought cycles (see U.S. spring wheat, Comment No. 20). (2)

21. Even chance—no breakthroughs, rate same as past. Upper limit—possible breakthrough. Lower limit—energy limited. (2)

U.S. Spring Wheat

1. See Argentine corn, Comment No. 13. (4)

2. Spring wheat is grown in areas highly dependent upon fallow and summer moisture; therefore, one would expect variability from year to year. This would be offset by development of grain which will withstand more stress and by improved farming practices. (4)

3. Path 1 (lower) indicates yields will be at least above the 1972-76 average with some increase. Path 2 indicates less increase than over the past 20 years. Path 3 (upper) indicates extrapolation of long-term trend since 1950. (4)

4. Main potential for increased yields is through varietal improvement. Increases of 7.5 percent, 15 percent and 30 percent, with respective cumulative probabilities of 0.1, 0.5 and 0.9, are projected for the year 2000. The 15 percent corresponds to gains over the past 60 years while the 30 percent corresponds to gains over the past 20 years. The base yield is taken to be 25.7 bu/acre. (4) References: Response of Winter and Spring Wheat Grain Yields to Meteorological Variation, Feb. 1977; Planting Date and Wheat Yield Models, Sep. 1977; both by A. M. Feyerherm, Department of Statistics Kansas State University. (*Editor's note:* These references were cited for all nine wheat crops.)

5. Higher line to 42 bu/acre is technically possible. Where is the market? (4)

6. *Editor's note:* Two panelists referred to their remarks on U.S. winter wheat (Comments No. 7 and 8). (4)

7. U.S. spring wheat yields are limited by climate; mainly rainfall, but a small shift in temperature will not shift U.S. spring wheat production away from its present area. (4)

8. Technology in the next decade will be a function of the market price of wheat, which in turn will depend on supply and demand. High farming costs, government programs (acreage reduction) and fertilizer costs will also play a role to stabilize yield for the next decade. Meanwhile, breeding program should manifest itself and lead to a gradual increase in yield in the second decade. (4)

9. Expect little technology change. Shift in acreage due to prices or programs causes the small expected changes which I have indicated. (3)

10. Varietal improvement should continue and may help yields more than expected. (3)

11. Dramatic changes in weather-control technology (precipitation and hail) could cause positive response. Added irrigation could help too. (3)

12. The descending lower line assumes further northward expansion of winter wheat production, confining spring wheat production to most northerly of the current U.S. production zones. A net reduction in yield per acre would probably result. This line also assumes limitations (environmental or economic or both) in the use of nitrogen fertilizers for spring wheat production. Upper line assumes stabilized winter wheat production zones or even an expansion of spring wheat zones southward because of increasing demand for spring wheat milling characteristics and quality. Varietal improvement, suppressed photorespiration, development of N-fixing organisms for wheat, and reduced weed competition might lead to modest yield increases of the type depicted. The horizontal midline is the likely result of positive and negative factors described above. (3)

13. The principal factor limiting U.S. spring wheat is moisture. The weather-induced yield variability is 14 percent. Without increase in precipitation there is little prospect for significant yield increase. (3)

14. Median path: through 1980 yields increase faster than in the past two decades because of the expectation for retiring marginal lands, then increase slowly to 32 bu/acre by 2000. Upper path projects the historical rate, after 1980. Lower path reflects no change in technology. (2)

15. Better moisture usage and heat resistance in new hybrids will increase yields. The loss of up to 30 percent to pests and weed problems will be reduced over the next 25 years. (2)

16. The high line is based on continuing the rapid increase in U.S. spring wheat yield accomplished since 1954 with the help of increased fertilizer. The most probable line is given a slope that is significantly upward but quite a bit less than the technologically optimistic high line. (2)

17. Yields will continue as in Canada (see Canadian wheat, Comment No. 6). (2)

18. Even chance—no breakthroughs, rate same as past. Upper limit—possible breakthrough. Lower limit—energy limited. (2)

19. Energy shortage will eventually have its toll. Expanded acreage will bring in low-yielding marginal land. (2)

20. The trend lines are dominated by the uncertainty in projecting effects of a 22-year drought cycle on the yields. (2)

21. See U.S. winter wheat, Comment No. 23. (2)

22. Spring wheat yields in the north central states will increase at a slower pace than in Canada because the climate is slightly more extreme and because improved technology has been applied to a greater percentage of the present acreage in the U.S.; therefore, there is not as much room for improvement. More confident of the yield trend in the U.S. as indicated by the closeness of the 1-in-10 paths. (See Canadian wheat, Comment No. 11.) (2)

USSR Spring Wheat

1. Varietal improvement increases of 7.5, 20 and 40 percent, with cumulative probabilities of 0.1, 0.5 and 0.9, are projected for the year 2000. Base yield is 16.5 bu/acre. (4) References: see U.S. spring wheat, Comment No. 4.

2. USSR spring wheat yields are quite low relative to those for Canada and the U.S. (USSR has lagged U.S. and Canada in introducing modern technology, e.g., mechanized farm equipment, fertilizer application; also, increased fallowing could lead to higher yields. Therefore, they can be expected to rise, although not to the level of Canada and the U.S., because of a less favorable climate (see Canadian wheat, Comment No. 3). (4)

3. The Russians have not exploited the application of fertilizer as much as it could be, although indications are that there is a trend toward this. Fertilizer plus new varieties should lead to an increasing trend in the late 1970s and continue at a slower rate in the 1980s. (4)

4. Soil-warming mulches, water-conserving technology, and possible weather modification (rain and hail) could cause increases. (3)

5. Path 1 (lower) shows that no decrease is expected. Path 2 shows less improvement than experienced in the last 20 years, when fertilizers were introduced. Path 3 (upper) shows same trend experienced in past 20 years. (3)

6. The main limiting factor for increasing USSR spring wheat production will be climate—both temperature and precipitation. I expect yields to increase about 1 percent per year over the next 25 years because of the marginal lands being brought into production. (3)

7. Similar to Canada, severe temperature and moisture limitations for wheat production occur in the USSR. The weather-induced yield variability for USSR spring wheat is the largest for any of the crops or countries in this study, 22 percent. There is only slight improvement in yield possible without a change in the climate. (3)

8. Reflects an expectation for continued improvement in technology through 1980 or 1990. By this time the technology should have "caught up" with the climate and a reduced rate of increase result. Lower limit reflects a constant technology. (2)

9. I can only guess as to the future of spring wheat. (2)

10. Spring wheat in Russia is grown in an area with highly variable rainfall, and year-to-year variability of yields will be quite large. New, improved varieties and improved farming practices will add a moderate increase to the average yields. (2)

11. The even-chance line more closely approaches the high line for USSR spring (and winter) wheat because I believe detente will continue and help provide the Russians outside technological advances in addition to their own. I also assume the Russian political system will change slightly in the direction of providing Russian farmers with more incentives for improvement. (2)

12. A gradual increase will continue, but variability will also continue to be high. (2)

13. Same line of reasoning as in U.S. spring wheat, Comment No. 9. (2)

14. With soil moisture the limiting factor, there is little way to increase yields except with varieties that would yield more in good years. (2)

15. The USSR is attempting to increase production mainly by adoption of better technology. If they can ever get away from central control of agriculture, they probably can come near the U.S. in yield. The day-to-day management decisions on the farm cannot be made in Moscow (or in Washington). The massive bureaucracy (separate ministries for Tractor Design, Tractor Manufacture, Implement Manufacture, etc.) in the USSR makes any rapid advance in agricultural technology improbable. Further, the variability inherent in yields of this crop (compare with U.S. spring wheat), which apparently is caused by more variable weather, makes application of technology more difficult. "There ain't no free lunch" in cultural practices, but it does "cost" less with a less variable weather regime. (2)

16. Upper line—with improved technology and varieties I anticipate a lower rate of yield improvement in the Soviet spring wheat zone because of (a) severe climate limitations with respect to growing seasons and interannual variability, and (b) societal difficulties in implementing advanced technology in a collective system. The slowly descending lower line assumes technology advances are modest and fertilizer supplies limited to the Russians by costs of energy for production of fertilizers and chemicals. Best guess is a 2-bu/acre increase by 2000. (2)

17. Improved drought- and cold-resistant varieties, increased fertilizer use, spring wheat moved further south; increase will be near-term with a leveling off or decrease in later years. (2)

18. The USSR spring wheat area would seem to have the climate and soils to match presently existing wheat production in the U.S. and Canada. The trend lines indicate more than anything else the level of priority which the USSR puts on supplying the needed inputs to increase their production. (2)

19. Variability in wheat yields over the last 25 years similar to Canada. Therefore, family of paths drawn in a similar fashion (see Canadian wheat, Comment No. 11). Confidence in predictions is low because of extreme year-to-year variability. (1)

WINTER WHEAT

Argentine Wheat

1. Wheat is grown in areas of Argentina with highly variable rainfall and a highly frequent drought occurrence. I would assume that overall yields would remain around 25-bu/acre level through combination of improved varieties and technology. (4)

2. In the next few years and through the 1980s, the position of the agriculture sector of the Argentine economy will be strengthened. Fertilizer application should also be on the rise as growers determine its impact to be economically feasible and beneficial. Yields should level off in the 1990s. (4) References:

(a) Sakamoto, C. The Z-Index and Subitaneous Events as Variables for Estimating Wheat Yield in Argentina; Technical Note 76-4. Center for Climatic and Environmental Assessment, NOAA, November 1976.

(b) Aizcorbe, R. *Argentina: The Peronist Myth;* Exposition Press, Hicksville, New York, 1975.

(c) Hutchinson, J.E., Urban, F.S., and Dunmore, J.C. Argentina: Growth Potential of the Grain and Livestock Sectors; Foreign Agricultural Economic Report No. 78, ERS, USDA, 1972.

(d) Paz, A.C., and Ferrari, G., *Argentina's Foreign Policy 1930–1962;* University of Notre Dame Press, Notre Dame, Indiana, 1962.

3. If increased fertilizer is used, yield will increase dramatically (upper line). Any irrigation will also improve yields in this time (probably greatest after 1990). Otherwise, yield might go up to average at the previous high. (3)

4. The main source of increased yields is assumed to be varietal improvement with 7.5-percent, 15-percent and 30-percent increases by the year 2000 having respective probabilities of 0.1, 0.5, and 0.9 for lesser increases. Base yield is 23.3-bu/acre. (3) References: see U.S. spring wheat, Comment No. 4.

5. See Argentine corn, Comment No. 7. (3)

6. Wheat production in Argentina is likely to increase at about 2 percent per year, but it could be as low as 1 percent and as high as 5 percent. These differences will depend on technology development and application. (3)

7. The weather-induced variability for Argentina wheat is 15 percent; moisture limits yields, and only modest yield improvement is possible without additional precipitation. Argentine wheat yields already are relatively high; while there is some potential for improving yields, the recurring droughts will not allow yields to increase to 30 bu/acre by 2000. (3)

8. Increased yields expected based on the expectation for additional fertilizer. The upper rate is based on a continuation of current trend while the lower limit is based on no change in technology. (2)

9. New semi-dwarf varieties are just being introduced (Hutchinson et al. Argentina: Growth Potential of the Grain and Livestock Sectors; Foreign Agr. Econ. Report No. 78, ERS, USDA, 1972), and their effect should be felt in the mid-70s. These will, perhaps, allow more effective use of fertilizers. Mechanization is already fairly advanced. (2)

10. The Argentine wheat yields have risen faster in the last 6 years than most of the last 26 years. This increase can be sustained at a slope with increasing fertilizer over the next 10 years or so. Then, other improvements like improved varieties may sustain a relatively fast increase. (2)

11. Argentine wheat yields should show a slow increase as new methods are adopted and fertilizer use increases. The past performance, however, indicates that the yields will fluctuate widely. (2)

12. I expect rather small increases in technology. A cutback on acreage should result in generally increased yields per acre. If prices are very low, no additional

technology will be used and yields will remain at same level. (2) References: (a) Research Report No. 56, ARS, USDA, 1962; (b) Thompson, L.M. Evaluation of Weather Factors in the Production of Wheat; *J. of Soil and Water Conservation*, July-August 1962.

13. More nitrogen could improve yields in years with ample moisture. (2)

14. Level trend is unlikely although possible because of lack of fertilizer use (lower path). An increase to 30 bushels is quite possible since it would be near the U.S. level of recent years. A 40-bushel level is unlikely by 2000 because of the high cost of fertilizer (upper path). (2)

15. The Argentine wheat area generally receives adequate rainfall. Disease susceptibility will probably be a very serious problem and limit increases to a moderate level. Fertilizer will become increasingly available, giving rise to a rapid potential increase in yield. I suspect economics will limit the realized increase to the 35 bu/acre indicated by the median trend line. (2)

16. Since the variability from year to year is not as great as some countries, e.g., Canada, it appears the climate is more stable and trends for increase not great, although there should be a steady improvement particularly continuing to 1980, and then a more gradual increase to about 38 bu/acre by the year 2000. (2)

17. *Editor's note:* Two panelists referred to their remarks on Argentine corn (Comments No. 2 and 19). (2)

18. Yield increases will occur because of fertilizer adoption, and rapid adoption could occur if fertilizers are available (energy problems?). (1)

Australian Wheat

1. This area is probably the most variable of agricultural regions and although good years will occur in terms of preciptation, technology is approaching a limit. (4)

2. Technology in Australia has remained relatively stable since 1950; however, there is no reason to doubt that new varieties plus increasing fallowing could provide a gradual increase in yield by the year 2000. (4) References: (a) Nix, H. A., and Fitzpatrick. An Index of Crop Water Stress Related to Wheat and Grain Sorghum Yield; *Agricultural Meteorology* 6 (5): 321-337, 1969; (b) Sakamoto, C. M. An Index for Estimating Wheat Yield in Australia; Center for Climatic and Environmental Assessment, NOAA, Columbia, Missouri, November 1976.

3. With water the overriding limiting factor, why expect change? (3)

4. Water improvement would be best chance for increase. I don't know if more irrigation supply is available. (3)

5. The main source of increased yields is assumed to be varietal improvement with 0-percent, 15-percent and 25-percent increases by the year 2000 having respective probabilities 0.1, 0.5 and 0.9 of lesser increases. Base yield is 18.6 bu/acre. (3) References: see U.S. spring wheat, Comment No. 4.

6. I expect Australian wheat yields to increase at about 3 percent per year and no more than 5 percent because of the limited climatic resources on that continent. Currently wheat is grown on the more marginal croplands and I see no reason to expect otherwise. (3)

7. The weather-induced wheat yield variability is 15 percent; however, about 1 year in 8 is a near disaster with yields near zero. There is little evidence to support much increase in Australian wheat yields; all available technology is presently being used, and the increase to the year 2000 will be almost nil. Drought is the climatic factor responsible for the low wheat yields in Australia, and irrigation is generally not feasible. (3)

8. Wheat yields in Australia have not improved over the past 25 years at as high a rate as for the other countries with a "developed" agriculture. The rate of increase over the next two decades should be improved and this is reflected in the upper limit and average projections. (2)

9. The rate of increase of Australian wheat yields is shown to be rather slow because of no expected breakthrough in new technology. The increases are developed from more fertilizer, improved varieties, and improved cultivation techniques. (2)

10. Australian wheat yields have been extremely erratic because of the low moisture availability, so there is little hope for dramatic yield increases. There should, nevertheless, be a gradual increase, but variability will likely also increase unless there is a change in breeders' attitudes toward more stability. The latter direction would probably mean lower yields in the long run. (2)

11. Water is so limiting that yields probably can't increase much. (2)

12. Most likely technology trend shows very little increase; if prices low, could be a small decrease. Under favorable price situation, could be a large increase in technology. (2) References: see Argentine wheat, Comment No. 12.

13. Yields are unlikely to trend downward since the present trend is upward slightly (lower path). The most likely trend will be an increase of 25 percent by 2000. The high cost of technology in a marginal climate will probably prevent a 50-percent increase by 2000 (upper path). (2)

14. The Australian scientific research establishment is excellent. Breeding of improved varieties is very likely to continue. My top path reflects the possibility of yield breakthroughs, especially suppression of photorespiration and development of N-fixing organisms symbiotic with wheat. The midline indicates lesser effects of the above-mentioned technologies and possible breakthroughs. The downward concavity of the bottom path reflects the possibility of severe energy shortages, requiring reduction in fertilizer production, especially nitrogen. (2)

15. Slight improvement due to improved drought resistance. Superphosphate use continues. Increased acreage will be in very marginal areas—decreased yields. (2)

16. Rainfall limitations are too severe to expect any rapid improvement in yield. (2)

17. Worn-out soil makes Australia particularly sensitive to the cost and availability of fertilizer, i.e., energy cost. (2)

18. Variability of Australian precipitation makes it difficult to project the effect of changes in management on crop yields. They are likely to be still below the 25-bu/acre level by the year 2000 in spite of application of fertilizers, new varieties and other improved technologies. Increases will not be as great as Canadian wheat yields because the Australian soils are not as naturally fertile as in the Canadian Prairies. (2)

19. See: (a) An Index for Estimating Wheat Yield in Australia; CCEA Technical Note 76-3, 1976; (b) Cornish, E. A. The Influence of Rainfall on the Yield of Wheat in Southern Australia; *Australian Journal of Scientific Research, Series B, Biological Sciences*, 33 (1959), 178-218. (1)

20. Technology adoption well along and rate is not great (climate is limiting). Present rate with slight increase is most likely (average) trend. (1)

21. Technology is not the constraint. Soils and fertilizer economics are. (1)

Indian Wheat

1. The median trend path (continuous line) has been drawn taking into consideration (a) static crop yield from start of fifties to mid-sixties, (b) a big jump in the yield in the late sixties which occurred mainly because of the introduction of high-yielding dwarf varieties and (c) a plateau-type trend after the peak yields of 1971 and 1972. The upper and lower dotted lines are fiducial limits at 90 percent. (Expertise = 4, assigned by project staff)

2. Percentage under irrigation and percentage planted to high-yielding varieties are assumed to have peaked. Increases in amount of nitrogen used and improved varieties are possible. Increases of 0 percent, 20 percent and 40 percent with respective cumulative probabilities of 0.1, 0.5 and 0.9 were projected for the year 2000. Base yield is 19.5 bu/acre. (4) References: see U.S. spring wheat, Comment No. 4.

3. Lands most suitable to high-yielding varieties (HYVs) were planted to those varieties in the late 1960s and early 1970s. New lands planted to HYVs do *not* show the considerable yield increases observed in the earlier plantings. Some yield improvement is likely as HYVs diffuse throughout India, but the increase should be small. Increases would be larger if currently marginal lands were adequately irrigated and fertilizer prices remained at current levels (upper curve). The lower curve follows from the assumption that fertilizer prices rise significantly in response to decreasing petroleum availability. It is my opinion that India, faced with these constraints, is already very close to its maximum yield levels. (4)

4. Precipitation in northern India has decreased since the introduction of high-yielding varieties (HYVs) in the 1960s led to higher yields. The decreased precipitation has not permitted the realization of potential yield with HYVs. Increased irrigated areas have led to a higher yield trend in the past few years. Therefore, the increased yields are attributed to increased irrigation, the rate of which should decrease with time. On the other hand, technology plus the return of increased precipitation to pre-1960 norms should increase yields substantially higher than the median 26 bu/acre indicated for 2000 AD. (4)

5. Indian wheat yields are increasing due to a number of factors—varieties, fertilization and irrigation. I expect this trend to continue in the future at a slow, gradual pace. (3)

6. Increased use of fertilizer and irrigation would be principal technologies. Both require much energy. Assuming a steady increase in inputs seems most optimistic (upper path). Middle path to 23 bu/acre assumes lesser input. (3)

7. Top path assumes expansion of high-yielding ("green revolution") varieties but limits determined by heavy chemical, fertilizer and water requirements of these varieties. Midline to 22 bu/acre assumes slow, steady conversion to high-yielding varieties, accompanied by continual broadening of gene pool to provide disease and

insect resistances which may limit the expansion of high-yield potential. Bottom line assumes limit to water-supply expansion by 1990—due either to nonavailability of transferable water supplies or to prohibitive costs of energy for water distribution. India's population problems militate against rapid improvement of per-acre productivity, which can only be achieved by the introduction of more large landholdings, or cooperative land management schemes. (Peasant agriculture with limited resources is unlikely to permit major yield increases to be achieved.) (3)

8. I feel that India will increase wheat production about 2 percent per year. It is probably technically possible to increase it by at least 5 percent, but Indian production could fall to less than 1 percent per year, due largely to the marginal land areas. Again, it is a question of human resources as well as the adoption of available technology in India. (3)

9. The weather-induced yield variability for Indian wheat is relatively low, 11 percent. There is ample room for increased fertilizer usage along with improved varieties so that considerable improvement in wheat yields is possible in India. There also is considerable potential for increasing the irrigated wheat acreage in India. (3)

10. Trends based on the same relationship to U.S. yields over the next 20 years (see U.S. winter wheat, Comment No. 17). Lower limits based on no change. (2)

11. The future of Indian wheat seems to be dependent on continued advances in irrigation and fertilizer. The point of diminishing returns may not be too far off. High temperature in December and January place an upper limit on yields, as well as soil fertility. As of 1972-73 only 35 percent of the area was sown to the high-yielding varieties. Increases will be expected as this percentage increases. (2)

12. The high-trend line indicates,what could happen to Indian wheat yield if technology at a high U.S. level could be applied to all Indian wheat. The realities of fast-rising energy costs will keep the actual yield increase at a substantially lower rate. India will also shift more wheat to newer high-yielding varieties and irrigation as she strives to match her food production to her fast-growing population. (2)

13. Indian wheat yields should continue to increase at a fairly fast rate because the climate is favorable. An improvement in the social conditions would no doubt result in a dramatic yield increase. (2)

14. Expect trend to be flatter than in earlier years (50/50). Potential decrease (1/10) is smaller than possible increase (1/10). (2)

15. Indian wheat yields have jumped recently due to new varieties which have been widely introduced. This increase is unlikely to be sustained at the same rate, but nitrogen could become more widely available. (2)

16. High projection based on all of India becoming at least as sophisticated as Punjab. I am afraid cultural mores, religion, sociology and politics will not let the high estimate occur. (2)

17. Decreasing fertility of soils. Poor prospects for obtaining necessary fertilizers. Increased acreage not likely, certainly will be on poorer land. Adequate mechanization unlikely. Hence the decline in yields indicated by the median path. (2)

18. The area involved is large enough to average out climatic variations. I would expect only slow increases in yield, however, due to economic limitations which are not likely to improve rapidly. (2)

19. When the energy supplies go, so will India. (2)

20. My knowledge of production practices in India is very minimal. No doubt new varieties and technology improvement ("green revolution") caused upswing of yields in late 1960s and early 1970s. That trend could not continue. Therefore, trends over the past 25 years should continue to about 1990, with another slight upswing occurring by about 1990 when new Centers of Agricultural Research established over the last 10 years should make significant contributions with respect to new varieties and other technological improvements. One-in-ten paths fall between Argentina and Canada. (2)

PRC Winter Wheat

1. For winter wheat the spring moisture is very critical and the frequency of dry years negates any large increases in yield. (3)

2. Fertilizer increase could produce upper line. Slowness to realize benefits of mechanization would produce 27 bu/acre by 2000 (center line). (3)

3. Potential for increase in yields by irrigation, increased nitrogen application, and varietal improvement. Increases of 10, 25 and 50 percent with respective cumulative probabilities 0.1, 0.5 and 0.9 were projected for the year 2000. Base yield is 20.8 bu/acre. (3) References: see U.S. spring wheat, Comment No. 4.

4. As with Chinese rice (Comment No. 1), the trend of winter wheat yields in China to the year 2000 should also show a rising trend. However, the slope of the trend should not be as steep as that for rice because China has given more emphasis to rice production than to wheat. The best croplands are always devoted to rice where feasible. (2)

5. Estimates were made based on the ratios to U.S. winter wheat yields. (2)

6. These PRC winter-wheat trend lines have been made quite similar to the lines for Indian wheat because both nations have the common challenge of transferring new technology to an enormous number of small farmers. India has the advantege of utilizing quickly the advances at the international research institutes, while China has the advantage of more organization in its political system and a strong commitment to feed its masses. (2)

7. Yields should show a sharp rise because they are currently lower than they should be for the climate. Introduction and development of new cultivars and technology will be the reason for the increase. (2)

8. Political stability will not continue to increase yields at the rate realized in last 10 years (2)

9. Chances of maintaining past trends only 1/10, but still expect a gradual increase over time. (2)

10. Yields should continue at nearly the present trend unless nitrogen fertilizer is introduced in larger amounts. (2)

11. Path 1 (lower) indicates that some increase is expected. Path 2 indicates 20-percent increase, which is more likely because the need will generate some technology. Path 3 (upper) indicates a possible 50-percent increase but this is unlikely due to lack of nitrogen fertilizer. (2)

12. Technology will rapidly increase. Chemical fertilizer, especially ammonia, will be more available and widely used. Mechanization is, and will continue, rapidly increasing. Most machinery will be imported at first. (2)

13. I see only slight improvements possible in PRC wheat yields because new lands will be very marginal climatically. Further, wheat is produced in areas where other food grains cannot be. Climate is chief limiting factor for increased yields. (2)

14. Appears that most efforts to increase total production (double cropping, for example) will result in smaller yield per acre. (2)

15. Wheat-yield trend lines are drawn to parallel those expected for U.S. production. (2)

16. The weather-induced variability in PRC wheat yields is quite low, 10 percent. This is nearly as low as the value for parts of western Europe where conditions are ideal for wheat; perhaps the PRC wheat-yield statistics are not too accurate. There is, however, ample room for a considerable increase in PRC wheat yields over the next few decades. Fertilizer, especially nitrogen, and improved varieties will be the keys to yield improvement in the PRC. (2)

17. Technological advances in China are likely to start leveling off in the 1980s, but by the 1990s a greater degree of freedom of choice and incentives for private breeding and managers should provide a spurt in yields in the 1990-to-2000 period. (1)

U.S. Winter Wheat

1. See Argentine corn, Comment No. 13. (4)

2. Winter wheat yields in the selected states are subjected to a variety of inputs which may affect winterkill, fall growth or spring growth. This variability in the natural conditions would cause yield levels to increase only slightly by the year 2000. (4)

3. Upper curve assumes research breakthrough in crop-climate interaction (new management or variety). Also assumes breakthrough in hail and precipitation control. Median path levels off at 30 bu/acre. (4)

4. Path 1 (lower) is a slight increase with a high probability of some increase. Path 2 is a continued uptrend with some leveling near 35 bushels. Path 3 (upper) is an extrapolation of the overall trend since 1950. (4)

5. Lower trend line assumes no increase in applied nitrogen but a 7.5-percent yield increase by the year 2000 due to improved varieties. Base yield is 24.5 bu/acre. Middle trend line assumes an increase of 15 pounds/acre in applied nitrogen (=2.5 bu/acre) and a 20-percent increase due to improved varieties. Thus,

$$1.20\ (24.5 + 2.5) = 32 \text{ bu/acre}$$

Top trend line assumes an increase of 15 pounds/acre in applied nitrogen and a 40-percent increase due to improved varieties. Thus,

$$1.40\ (24.5+2.5)=38 \text{ bu/acre. (4)}$$

References: see U.S. spring wheat, Comment No. 4.

6. We could see more double cropping in what is now the corn belt. But single-cropped wheat in the corn belt has much higher yields than the states indicated. Also, see comments on U.S. spring wheat (No. 5), U.S. soybeans (No. 15), and U.S. corn (No. 8). (4)

7. There is strong evidence that U.S. crop yields (especially wheat) have leveled off or, at least, are beginning to level off. With future energy shortages (and related higher costs), possible decreases in fertilizer application rates may even lead to a decrease in yields. (4) References: (a) Thompson, L. M., in *Science* Vol. 188 (1975), 535-541; (b) Katz, R. W., et al in *Environmental Data Service,* July 1975, 10-15.

8. Upper line—new varieties exhibiting both increased rust resistance and fertilizer sensitivity adopted. Worldwide demand increases prices, so fertilizer costs are not limiting until around 1990. Middle line to 30 bu/acre—no net increase in demand. Lower line—no substantial change in varieties planted. Modeling the technological component is a risky enterprise at best:

(a) How can one anticipate technological breakthroughs?

(b) Technological factors interact strongly with climate.

Perhaps best example of isolation of technology component is by Dalrymple (USDA 1975), but even that was "hind-" rather than "fore-" casting. (4)

9. Lower line assumes modest yield increases due to improving technologies until about 1990 when liberal use of nitrogen fertilizers in wheat production will become restricted due either to cost of nitrogen (N) or to environmental restrictions. (Increasing nitrate levels in Great Plains groundwater supplies are attributed to excessive N-fertilization and this trend is bound to worsen unless fertilizer application methods and quantities of N used are altered.) Midline to 27 bu/acre assumes that plant-breeding improvements and other technologies (weed control, e.g.) compensate for reduced N-consumption. Upper line assumes continued progress in wheat breeding which further decreases sensitivity to environmental stress of moisture shortage. Wheat has proven to be among the very most resilient of our crops—witness the remarkable yield in 1977 after planting in the dry soil of fall 1976 and the dry winter of 1976-77. Upper line also assumes no major restrictions in energy-consuming production inputs (mechanical and chemical). (4)

10. Increased yield in the U.S. winter wheat crop will be limited by climate, mainly the moisture factor. A drier climate would shift wheat production to the east and north while a wetter climate would shift the area to the southwest. Yield improvement is likely to continue to about 2 percent per year. (4)

11. Even chance—no breakthroughs, rate same as past. Upper limit—possible breakthrough. Lower limit—energy limited. (4)

12. See U.S. spring wheat, Comment No. 8. (4)

13. The apparent weather-induced U.S. wheat yield variability is nearly 20 percent; however, much of this is attributable to diseases. There is evidence for a leveling-off of U.S. wheat yields and only a modest increase is predicted for the next few decades. (4)

14. Same line of reasoning as for U.S. spring wheat (Comment No. 9), but greater changes possible as indicated by past variations. (3)

15. Varietal improvement in wheat is moving fairly rapidly. Nitrogen prices are a factor. (3)

16. Energy shortage will eventually take its toll, primarily in availability of fertilizers and required mechanization. Increased acreage would be obtained in shift from fallow cropping system to continuous wheat, producing a large decrease in yield. New drought-resistant varieties will provide some increase. Near-future increase in irrigation may also provide an increase. Doubt this can be maintained through 2000. Most likely trend path is horizontal. (3)

17. Median path: higher rate of yield increase through 1980 due to the retirement of marginal lands from production, then a slower rise to 31 bu/acre. Lower limit reflects no change in technology, while upper limit reflects a continuation of current trend after 1980. (2)

18. Already developed hybrids can raise yields 15–25 percent; further use of fertilizer, irrigation and pest control will also raise yields. (2)

19. These trend lines for U.S. winter wheat are set up very similar to those for U.S. spring wheat (Comment No. 16). These crops differ more in their locations and environmental conditions than they differ in their responses to new technology. (2)

20. Yields will increase but will continue to be erratic due to marginal moisture and occasional unfavorable winters reducing plant stands. (2)

21. Water problems may be biggest reason yields won't exceed 35 bu/acre. (2)

22. Much of the winter wheat area is subject to limitations in yield due to drought. While improved varieties, fertilizer and pesticides will probably result in an increasing trend line, I believe there is at least a 1-in-10 chance that little further improvement is possible and this is shown by my lowest trend line. An 11- and 22-year drought cycle seems appropriate for the lowest yield trend line. The 11-year cycle is assumed to be missing on both the average and highest trend line. The 11-year cycle is assumed to be missing on both the average and highest trend line. At least a short-duration 22-year cycle is assumed for all cases. (2)

23. The technological aspects of trend are so convoluted with economic and political issues as to make any estimate largely a shot in the dark. The availability and price of energy are all-important. The breakpoint is placed at the next significant (order-of-magnitude) increase in energy costs. (2) (*Editor's note:* The lower curve bends down after 1980; the median path to 33 bu/acre has a 1985 breakpoint.)

USSR Winter Wheat

1. Lower trend line assumes an increase of 7.5 percent for varietal improvement and a base yield of 34.2, i.e., 37 bu/acre by 2000 AD. Middle trend line assumes an increase of 20 lb/acre for nitrogen (3.5-bu/acre yield increase) along with a 20-percent varietal improvement increase by the year 2000:

$$1.20\ (34.2 + 3.5) = 45 \text{ bu/acre.}$$

Top trend line assumes an increase of 20 lb/acre for nitrogen (3.5-bu/acre yield increase) along with a 40-percent varietal improvement increase by the year 2000:

$$1.40\ (34.2 + 3.5) = 53 \text{ bu/acre. (4)}$$

References: see U.S. spring wheat, Comment No. 4.

2. USSR winter wheat yields are quite high relative to U.S. winter wheat yields. However, they also exhibit a leveling-off pattern. Therefore, a similar trend pattern to that of U.S. yields should be expected in the future. (See U.S. winter wheat, Comment No. 7.) (4)

3. See USSR spring wheat, Comment No. 3. (4)

4. Continued use of fertilizer could put them near climatic maximum of 40 bu/acre (median path). Breakthrough in variety for improved climate-crop maximum in U.S. would be immediately transferable to Russia (upper path). (3)

5. Path 1 (lower) assumes some improvement. Path 2 assumes some increase but not as much as past 20 years. Path 3 (upper) assumes an extrapolation of trend of past 20 years. (3)

6. Technical applications are much more likely to be achieved in USSR winter wheat production than in spring wheat production. But climate will be limiting, mainly available moisture. (3)

7. The weather-induced USSR winter wheat yield variability is 13 percent, less than that for the U.S. I suspect the USSR yield variability really is somewhat higher. The projected yield increase is modest, just over 40 bu/acre by the year 2000. (3)

8. Upper limit reflects a continuation of the current trend. Median curve reflects the expected rate of change for the U.S. production area. Lower limit is based on constant technology. (2)

9. New hybrids will be fundamental to the increased productivity of Russian wheat. (2)

10. Winter wheat yields will be influenced by a combination of good weather in the fall, winter weather, and spring weather for the reproductive phase. If the weather remains constant until 2000, then I expect technology in terms of high-yielding varieties to offset the effects of poor years. (2)

11. The 45 bu/acre on the even-chance trend line for USSR winter wheat is based on my belief that it will be hard to find new technology to match the benefits of increased fertilizer and new varieties over the last quarter century. Yet, the Russians will probably be able to keep their absolute yields higher than those in the U.S. (2)

12. The dramatic increase in the past few years will begin to level off since the increase is likely derived mainly from sacrificing quality. The low USSR spring wheat yields don't justify a totally opposite response in winter wheat. Further winter wheat yields will come from more uniform adoption of the latest technology. (2)

13. See U.S. winter wheat, Comment No. 14. (2)

14. Recent increases represent new varieties. Use of more nitrogen could give future rapid rise. (2)

15. See most of commentary for USSR spring wheat (No. 15). Less variability is seen here than for spring wheat. A major problem with USSR projections is believability. When they claim a certain fertilizer rate, subtract 20-25 percent, as an example. Another general comment on USSR crop production: a large technology difference exists between the collectives and the state farms. I know of no one outside the USSR who can correctly assess this situation. (2)

16. Improved varieties and increased use of fertilizer will provide initial yield increases, but energy shortage and expansion of acreage into marginal areas will bring about declining yields. (2)

17. Rainfall in the USSR winter wheat region should be capable of sustaining higher usage of fertilizer and adoption of improved hybrids. The yield trend should continue at about its present rate of increase. (2)

18. Technological advances should result in a trend similar to the last 25 years. (1)

APPENDIX C–1

GROSS EXPERTISE VERSUS NET EXPERTISE

INTRODUCTION

In Section 4-9 we noted that the annual-yield data bases are somewhat superior to the technology data bases in terms of *net* expertise—the expertise associated with the responses that were actually incorporated into the data bases. On the other hand, if we examine *gross* expertise—how a panelist rated himself without regard to whether a response, if any, was considered acceptable—we note a contrary tendency. Namely, the average gross expertise is slightly higher for the technology questions than for the annual-yield questions.

THE GROSS AND NET EXPERTISE RATINGS

In Table C-1.1 we compare data on the gross and net expertise ratings for an aggregate of 495 = 15 × 33 two-part country-crop questions presented to the 33 panelists who submitted at least one quantitative reply. More often than not, a panelist gave himself the same rating on Part I (technology) and Part II (crop response to annual weather). In fact, 12 of the 33 panelists gave themselves identical technology and annual-yield ratings on all 15 country-crop combinations.

Table C-1.1

SUMMARY OF GROSS EXPERTISE AND NET EXPERTISE DATA

	Average Expertise		Number of Ratings		Pct Equal Ratings	
	Gross	Net	Gross	Net	Gross	Net
Technology (Part I questions)	2.16	2.67	495	287	75%	86%
Crop Response (Part II questions)	2.14	2.82	495	273		

The "GROSS" columns pertain to the expertise ratings irrespective of whether replies were placed in the data bases. The "NET" columns pertain only to replies that were incorporated into the data bases. The last column refers to the 207 pairs of Part I/Part II questions for which both responses were entered in the data base.

Table C-1.2

COMBINATIONS OF GROSS EXPERTISE RATINGS

		Technology							
		Part I reply, if any, not in Data Base				Part I reply in Data Base			Row Totals
ANNUAL YIELD FUNCTION	Expertise	1	2	3	4	2	3	4	
Part II reply, if any, not in Data Base	1	133	1			42	3	4	183
	2	2	3			14			19
	3		1	1		5	3		10
	4		1			2		7	10
Part II reply in Data Base	2	19	11	1		80	4		115
	3	2	4	15	1	10	54	7	93
	4			5	8	3	5	44	65
Column Totals		156	21	22	9	156	69	62	495

Combinations of self-ratings of expertise on the Part I portion (technology projections) and the Part II portion (crop response to annual weather) for each of 495 country-crop questions presented to the 33 panelists who submitted at least one quantitative reply. An expertise of 1 (unfamiliar) was assigned when a panelist failed to rate himself or recorded an expertise value of zero.

Table C-1.2 helps to explain the apparent paradox of the gross and net expertise averages. This table contains tallies of the Part I/Part II pair of ratings segregated according to whether the Part I reply or the Part II reply, if any, was put into a data base. For example, there were 14 instances such that (1) the panelist rated himself "Familiar" (expertise = 2) on both parts of a country-crop combination, and (2) his Part I reply was aggregated into the technology data base, but (3) his Part II response (if he submitted one) was disqualified for one reason or another.

Looking at the diagonal entries in the four subsections of Table C-1.2, one notes 373 country-crop opportunities—75% of the total—which carry the same gross expertise rating on both portions of a question. Tipping the scale of *gross* expertise toward technology are 63 above-the-diagonal cases, for which the Part I expertise exceeds the Part II expertise, compared to 59 left-of-the-diagonal gross-expertise combinations, which favor the Part II question. In addition, the panel as a whole had a greater "familiarity" with the technology questions than with the annual-yield questions; in 339 cases panelists rated themselves "Familiar" or better on a technology question versus 312 cases of like ratings for annual-yield questions.

Thus, disregarding whether their responses were incorporated into the data bases, one could argue that the panelists felt slightly more competent in the technology area.

THE REVERSAL OF EXPERTISE IN THE DATA BASES

The actual data bases present quite another picture: the average *net* expertise favors the annual-yield data bases rather than the technology data bases. The reversal of expertise occurs for a number of reasons. In the first place, there were 183 annual-yield ratings of "Unfamiliar" compared to 156 technology "Unfamiliars."[1] None of these cases is eligible for a data base, so none has any effect on *net* expertise, but all the cases depress the average of *gross* expertise, and this depressant effect is greater on the annual-yield questions than on the technology questions.

Even when eligible by virtue of gross expertise to make a contribution to a data base, some panelists rendered no reply. Others submitted replies that could not be used, either because the questions were misinterpreted or because the answers were incomplete or inconsistent. If we consider only the requirements on which the panelists rated themselves 2 (Familiar) or better, then the average gross expertise is 2.69 for the technology questions and 2.81 for the annual-yield questions. These adjusted *gross* expertise averages, based solely on "eligible" ratings, are very close to the average *net* expertise values listed in Table C-1.1. This circumstance is confirmation that the lower gross expertise of the Part II questions in the first column stems primarily from the excess of "Unfamiliar" ratings. It also suggests that blank answer sheets together with discarded responses had about the same effect on both data bases.

Focusing now on the cases for which either a Part I or Part II response, or both, went into a data base, we can pinpoint additional reasons for the higher net expertise of the annual-yield data bases. In Table C-1.2, there are 42 country-crop replies in the technology data bases—about 15% of all the entries—for which the expertise is 2 (Familiar) and for which the corresponding annual-yield expertise is 1 (Unfamiliar). These 42 cases, of course, depress the average of *gross* annual-yield expertise but they are not charged against the average *net* expertise of the annual-yield data bases because "Unfamiliars" are ineligible. However, these cases do depress the average *net* expertise of the technology data bases because they carry the lowest eligible expertise rating. Countering the 42 cases which work to the detriment of the net *technology* expertise are only 19 analogous cases which work against the net *annual-yield* expertise, i.e., about 7% of the entries in the annual-yield data bases carry an expertise of 2 with a corresponding technology expertise rating of 1. Also working to the relative advantage of the net annual-yield expertise is the excess of the 18 below-the-diagonal cases in the lower right-hand subsection of Table C-1.2 over the 11 above-the-diagonal cases.

In the lower right-hand subsection of Table C-1.2, there are 207 two-part country questions—72% of the 287 entries in the technology data bases and 76% of the 273 entries in the annual-yield data bases —for which both the Part I and Part II replies were included in the data bases. Of these 207 dual-inscription cases, fully 86% carry identical expertise ratings on Part I and Part II. Despite this core of responses from panelists who saw themselves as equally competent in the two subject areas, the average net expertise rating for annual-yield questions is about 6% higher than the average net expertise rating for technology questions.

SOME AFTERTHOUGHTS

The differences of expertise between the final technology and annual-yield data bases are due partially to loopholes in the crop-yield questionnaire (Appendix A-1). If our instructions had precluded some of the responses that we had to reject, the distribution of expertise might have been somewhat different. Most of these regrettable discards were (1) Part I responses with 10th and 90th percentile paths that didn't originate at the 1972–76 average yield, or (2) Part II responses with an incomplete Grid 2 that couldn't be filled out by interpolation.

Why did the agriculture panelists, who were selected primarily for their knowledgeability about the response of crop yields to annual weather, frequently rate themselves equally as expert with respect to agricultural technology? Undoubtedly, many were equally expert in both areas according to the definitions of expertise furnished in the questionnaire. We suspect, though, that some panelists found the Part I requirement of drawing yield-trend paths less onerous than filling out the yield grids in Part II. On Part I there were few ground rules for drawing the three paths corresponding to the 10th, 50th and 90th percentiles of yield. The panelist, assuming only constant climate, could devise his own economic-political scenario for each path. On Part II, however, he was faced with the more daunting task of writing down estimates for spatially averaged yields corresponding to 48 crop-weather states that were incompletely specified by only two variables. Therefore, the apparent ease of satisfying the Part I requirements, compared with the real difficulty of meeting the Part II requirements, may have influenced a number of the expertise ratings.

APPENDIX D–1

THE MASTER YIELD GRIDS

The normalized Master Yield Grids determine the annual-yield functions required for the climate-response model (see Sections 1-5, 1-8, 5-3, 5-4, 5-5). The grids were aggregated from the agriculture panelists' responses to the Part II questions in the crop-yield survey (Appendix A-1). The numbers and average expertise of the panelists represented in the data base of each key crop are shown in Figure IV-11 and Table V-2.

The grid cells are identified by the crop-weather variables ΔT and ΔP defined in Section 1-5. The first entry in each cell is the normalized weighted mean of the individual yields estimated for the given values of ΔT and ΔP. In our normalization scheme, this mean is expressed as a percentage of the crop's expected (or average) yield in the Base Period (the recent past). The next two entries concern the dispersion of the individual estimates. They are the coefficient of variability (the ratio of the standard deviation to the mean) and the skewness of the distribution of yield estimates.

YIELD GRIDS

Table D-1.1

CORN: *Master Yield Grids*

ARGENTINA

GRID 1

ΔT (°C)	-20	-10	0	10	20
	70.0	81.9	91.2	102.0	109.1
2	0.239	0.163	0.120	0.113	0.131
	-0.58	-0.66	-0.66	-0.36	-0.96
	76.7	88.7	97.8	106.3	114.1
1	0.158	0.092	0.053	0.069	0.103
	-0.47	-0.84	-0.65	-0.40	-0.75
	80.3	93.2	103.7	111.4	118.0
0	0.125	0.059	0.000	0.049	0.095
	0.28	-0.31	0.00	0.75	0.48
	85.2	97.4	106.7	115.1	122.8
-1	0.140	0.088	0.060	0.090	0.123
	0.34	-0.17	1.29	1.66	1.37
	86.2	98.9	109.4	117.4	128.4
-2	0.182	0.147	0.132	0.149	0.184
	1.09	0.77	1.36	1.58	1.03

GRID 2

	ΔP (%)				
	-80	-40	0	40	80
	8.2	26.1	63.9	96.1	97.8
6	2.060	0.997	0.442	0.380	0.436
	1.82	1.33	0.49	0.62	0.79
	13.3	40.9	86.1	117.2	112.1
3	1.062	0.572	0.214	0.220	0.311
	1.12	0.50	-0.33	0.06	0.06
	18.5	52.1	103.7	128.0	121.7
0	0.860	0.322	0.000	0.166	0.273
	0.77	-1.02	0.00	-0.45	-0.50
	31.3	64.8	105.7	125.0	111.3
-3	0.853	0.437	0.210	0.188	0.252
	0.19	-0.04	0.74	0.18	-0.76
	23.8	53.5	86.6	103.3	94.5
-6	0.930	0.548	0.405	0.380	0.366
	0.47	0.44	0.95	1.69	-0.28

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GRID 1

ΔT (°C)	ΔP (%)				
	-20	-10	0	10	20
	76.4	85.5	93.6	99.1	102.8
2	0.152	0.133	0.142	0.135	0.157
	-1.22	-1.07	0.28	2.07	2.69
	81.2	90.4	99.2	106.1	107.0
1	0.128	0.082	0.066	0.077	0.132
	-1.16	-1.47	0.16	1.93	2.56
	86.0	96.0	104.0	110.8	111.5
0	0.133	0.070	0.000	0.076	0.102
	-0.59	-1.50	0.00	1.97	1.27
	88.0	97.7	107.0	112.3	113.1
-1	0.139	0.088	0.069	0.118	0.122
	-0.18	-0.78	0.66	1.97	0.45
	87.1	96.6	104.7	109.2	111.2
-2	0.175	0.128	0.114	0.134	0.188
	0.56	0.50	0.72	0.94	0.75

GRID 2

	ΔP (%)				
	-80	-40	0	40	80
	14.4	33.0	66.6	77.1	78.8
6	1.361	0.733	0.505	0.410	0.436
	1.00	0.43	0.07	0.37	0.57
	20.5	49.1	86.9	99.4	95.6
3	1.059	0.446	0.256	0.172	0.308
	0.82	-0.15	-0.11	0.25	0.21
	26.0	62.7	104.0	112.8	102.3
0	0.920	0.333	0.000	0.188	0.292
	0.55	-0.88	0.00	1.30	0.18
	31.5	66.2	99.4	106.4	95.3
-3	0.897	0.362	0.216	0.282	0.350
	0.38	-0.30	0.94	2.14	0.64
	32.5	56.7	76.5	82.3	76.1
-6	0.998	0.539	0.423	0.416	0.491
	0.62	0.27	0.26	0.52	0.43

Table D-1.2

RICE: *Master Yield Grids*

INDIA

GRID 1

ΔT (°C)	ΔP (%) -20	-10	0	10	20
2	78.4 0.131 0.63	85.7 0.103 0.67	99.0 0.068 -0.12	103.5 0.087 -0.04	106.4 0.112 -0.24
1	81.8 0.075 0.21	88.7 0.066 0.47	101.4 0.033 0.12	105.9 0.061 -0.46	109.2 0.084 -0.42
0	83.0 0.046 1.49	92.7 0.000 0.00	103.0 0.000 0.00	110.0 0.020 0.52	113.6 0.045 -1.46
-1	85.6 0.071 -0.13	94.3 0.059 -0.16	103.0 0.058 0.00	109.4 0.069 -1.37	112.7 0.081 -1.84
-2	83.0 0.090 -0.19	93.6 0.112 0.39	104.1 0.118 -0.21	109.3 0.111 -1.19	115.0 0.123 -1.95

GRID 2

ΔT (°C)	ΔP (%) -80	-40	0	40	80
6	13.7 1.262 0.95	43.9 0.442 -0.71	79.5 0.144 -1.30	96.0 0.173 -0.45	95.6 0.458 -0.64
3	21.1 1.111 0.38	57.8 0.251 -1.59	95.1 0.110 0.18	110.2 0.168 0.02	103.9 0.401 -0.25
0	23.6 1.060 0.22	66.4 0.129 -0.55	103.0 0.000 0.00	117.3 0.118 -1.56	100.7 0.304 -0.27
-3	30.1 0.946 0.41	68.1 0.252 -0.58	103.6 0.153 -0.15	114.4 0.160 -1.16	102.4 0.229 -1.39
-6	27.5 0.745 0.01	62.6 0.335 -0.81	89.9 0.301 -0.30	94.8 0.232 0.48	84.7 0.348 -1.68

PRC

GRID 1

ΔT (°C)	ΔP (%) -20	-10	0	10	20
2	80.0 0.223 -0.22	87.8 0.164 -0.52	97.9 0.089 -0.32	106.2 0.111 -1.25	109.2 0.139 -1.04
1	85.1 0.163 -0.21	93.0 0.111 -0.72	101.2 0.045 -0.55	106.3 0.075 -1.32	109.5 0.103 -0.89
0	88.9 0.109 -0.06	96.8 0.062 -1.04	104.9 0.000 0.00	110.3 0.029 -0.04	112.6 0.063 -0.40
-1	89.2 0.100 1.73	96.9 0.062 1.39	104.2 0.051 0.16	107.5 0.061 -0.56	107.7 0.103 0.10
-2	89.0 0.140 0.98	96.4 0.117 0.28	102.7 0.104 0.03	106.2 0.107 -0.48	108.4 0.135 -0.29

GRID 2

ΔT (°C)	ΔP (%) -80	-40	0	40	80
6	35.8 0.847 -0.16	51.5 0.516 -0.34	83.3 0.168 -0.00	90.3 0.166 -0.70	82.3 0.485 -0.86
3	38.8 0.840 -0.21	70.2 0.245 -0.35	96.7 0.112 -0.35	104.8 0.147 -0.43	89.7 0.394 -0.44
0	36.5 0.826 -0.30	77.6 0.108 -0.87	104.9 0.000 0.00	111.7 0.093 -0.39	93.4 0.294 -1.38
-3	39.6 0.824 -0.07	70.1 0.163 -0.30	99.0 0.126 0.81	103.3 0.162 0.65	88.2 0.288 -0.69
-6	32.1 0.790 0.03	55.7 0.340 -0.25	72.8 0.252 0.04	73.1 0.226 -0.01	65.8 0.457 -1.29

Table D-1.3

SOYBEANS: *Master Yield Grids*

BRAZIL

GRID 1

	ΔP (%)				
ΔT (°C)	-20	-10	0	10	20
2	66.4 0.352 -1.24	79.2 0.223 -1.38	91.0 0.118 -0.99	97.8 0.102 -1.01	104.0 0.152 -1.74
1	75.0 0.246 -1.07	86.1 0.171 -1.02	98.2 0.051 -0.61	105.5 0.082 -1.09	110.7 0.149 -1.21
0	82.6 0.176 -0.32	93.8 0.104 -0.65	104.0 0.000 0.00	111.2 0.066 -0.99	115.2 0.146 -0.61
-1	85.2 0.172 0.36	95.7 0.102 0.40	105.6 0.066 0.46	110.4 0.097 1.01	114.1 0.189 -0.45
-2	85.3 0.209 0.75	96.0 0.141 0.13	104.6 0.136 0.74	109.0 0.189 1.41	113.5 0.260 0.59

GRID 2

	ΔP (%)				
ΔT (°C)	-80	-40	0	40	80
6	7.9 1.270 0.74	27.7 0.743 -0.06	54.9 0.369 -0.15	70.3 0.351 -0.05	77.5 0.527 0.46
3	14.2 1.009 0.58	44.2 0.515 -0.30	80.3 0.215 -1.03	94.8 0.242 -0.73	95.7 0.462 -0.04
0	24.2 0.988 1.06	60.5 0.387 -0.21	104.0 0.000 0.00	110.2 0.224 -0.86	102.4 0.472 -0.20
-3	25.7 0.817 0.67	61.8 0.396 1.69	101.8 0.257 1.42	105.4 0.366 1.09	97.0 0.477 0.30
-6	21.7 0.877 0.49	55.9 0.647 1.82	76.1 0.493 0.40	77.6 0.520 0.68	75.0 0.643 0.76

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GRID 1

	ΔP (%)				
ΔT (°C)	-20	-10	0	10	20
2	71.3 0.274 -0.36	84.5 0.170 -0.77	95.5 0.123 -1.31	102.7 0.098 0.04	107.4 0.140 0.16
1	80.2 0.192 -0.26	90.6 0.123 -0.86	100.8 0.054 -1.70	108.7 0.113 1.66	111.9 0.126 0.21
0	85.4 0.138 -0.10	95.8 0.059 -0.27	104.9 0.000 0.00	112.3 0.071 1.72	117.2 0.100 0.20
-1	86.0 0.142 -0.03	95.5 0.077 -0.64	103.5 0.068 -1.03	110.3 0.086 1.20	114.4 0.140 1.11
-2	82.7 0.168 -0.54	91.8 0.133 -1.13	99.9 0.139 -0.30	106.3 0.154 1.02	111.6 0.199 1.51

GRID 2

	ΔP (%)				
ΔT (°C)	-80	-40	0	40	80
6	18.7 1.220 0.89	38.3 0.643 0.23	70.9 0.269 -0.40	84.5 0.228 -0.31	85.9 0.338 0.17
3	24.8 0.979 0.66	52.9 0.465 -0.09	89.7 0.149 -1.30	110.6 0.182 0.73	100.5 0.313 0.78
0	31.9 0.872 0.32	66.7 0.340 -0.90	104.9 0.000 0.00	121.8 0.219 1.09	106.6 0.318 0.72
-3	34.9 0.862 0.28	65.2 0.382 -0.31	98.1 0.236 0.43	109.4 0.317 1.48	99.0 0.426 0.50
-6	29.2 1.018 0.58	51.6 0.517 -0.16	73.1 0.434 -0.22	81.5 0.492 0.69	76.8 0.591 0.57

Table D-1.4

SPRING WHEAT: *Master Yield Grids*

CANADA

GRID 1

```
                         ΔP (%)
          -20   -10     0    10    20
        ◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆
        ◆
        ◆  74.1  87.7 104.7 116.5 124.8
      2 ◆ 0.308 0.174 0.107 0.138 0.178
        ◆ -1.05 -0.12 -0.13  1.08  1.21
        ◆
        ◆  78.9  92.4 107.4 117.6 123.3
      1 ◆ 0.223 0.109 0.056 0.092 0.122
        ◆ -0.81 -0.58 -0.11  1.48  1.66
        ◆
 ΔT     ◆  82.3  94.1 106.7 114.1 120.5
 (°C) 0 ◆ 0.164 0.085 0.000 0.039 0.080
        ◆ -0.52 -0.66  0.00  0.59  0.47
        ◆
        ◆  79.3  90.8  99.7 104.1 106.5
     -1 ◆ 0.221 0.139 0.085 0.095 0.167
        ◆ -1.44 -2.02 -0.10  0.48 -0.93
        ◆
        ◆  69.1  77.6  85.1  92.9  94.0
     -2 ◆ 0.411 0.354 0.313 0.276 0.329
        ◆ -1.05 -1.26 -1.29 -1.65 -1.22
```

GRID 2

```
                    ΔP (%)
     -80   -40     0    40    80
   ◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆
   ◆
   ◆  17.5  44.0  81.6 123.2 135.2
 6 ◆ 1.814 0.733 0.341 0.314 0.379
   ◆  2.37  1.15  0.93  0.12  0.40
   ◆
   ◆  20.1  54.8  97.4 132.1 143.8
 3 ◆ 1.371 0.459 0.165 0.280 0.392
   ◆  2.25  0.51  0.75  2.76  2.68
   ◆
   ◆  22.5  60.6 106.7 126.4 133.2
 0 ◆ 1.155 0.373 0.000 0.118 0.198
   ◆  1.65 -0.50  0.00 -0.24  0.51
   ◆
   ◆  19.4  48.8  71.0  84.8  81.9
-3 ◆ 1.162 0.529 0.461 0.487 0.539
   ◆  1.65 -0.40 -0.09 -0.34 -0.38
   ◆
   ◆  11.1  23.8  34.6  42.2  46.1
-6 ◆ 1.598 1.178 1.195 1.121 1.076
   ◆  3.27  1.17  1.13  1.06  0.80
```

U.S.

GRID 1

```
                         ΔP (%)
          -20   -10     0    10    20
        ◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆
        ◆
        ◆  72.2  84.2  96.9 103.1 107.4
      2 ◆ 0.246 0.149 0.099 0.110 0.131
        ◆ -1.31 -1.24  0.10  0.45  0.36
        ◆
        ◆  79.3  88.9 101.4 108.3 112.8
      1 ◆ 0.186 0.108 0.059 0.070 0.111
        ◆ -1.38 -1.23 -0.33  0.96  1.01
        ◆
 ΔT     ◆  83.4  93.5 103.5 110.5 116.6
 (°C) 0 ◆ 0.154 0.072 0.000 0.055 0.099
        ◆ -1.06 -1.43  0.00  2.29  1.32
        ◆
        ◆  84.1  94.0 103.8 110.5 114.9
     -1 ◆ 0.165 0.106 0.058 0.075 0.103
        ◆ -0.69 -1.24  0.11  0.04  0.00
        ◆
        ◆  83.2  92.2 102.9 109.2 113.5
     -2 ◆ 0.198 0.155 0.112 0.109 0.138
        ◆ -0.47 -0.59  0.33  0.43  0.28
```

GRID 2

```
                    ΔP (%)
     -80   -40     0    40    80
   ◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆◆
   ◆
   ◆  19.4  42.0  73.1  94.1  98.5
 6 ◆ 1.124 0.527 0.308 0.351 0.399
   ◆  0.90 -0.21 -0.02  0.29  0.44
   ◆
   ◆  26.0  56.8  88.9 110.5 114.7
 3 ◆ 1.033 0.373 0.140 0.194 0.286
   ◆  0.41 -0.84 -0.01  0.70  0.28
   ◆
   ◆  32.1  67.4 103.5 121.8 124.5
 0 ◆ 0.969 0.342 0.000 0.165 0.260
   ◆  0.29 -1.10  0.00  0.79  0.28
   ◆
   ◆  33.2  70.6 100.3 113.7 112.8
-3 ◆ 0.954 0.353 0.174 0.209 0.280
   ◆  0.38 -0.68  0.19  0.58  0.17
   ◆
   ◆  25.7  49.9  75.7  90.2  90.1
-6 ◆ 0.995 0.552 0.382 0.383 0.395
   ◆  0.62  0.01  0.03  0.15  0.11
```

Table D-1.5

SPRING WHEAT: *Master Yield Grids*

USSR

GRID 1

ΔT (°C)	ΔP (%) -20	-10	0	10	20
2	68.8	84.7	107.5	112.9	121.0
	0.268	0.148	0.117	0.122	0.174
	-0.90	-0.54	0.42	0.42	0.47
1	74.2	90.1	108.4	115.3	120.9
	0.212	0.108	0.063	0.080	0.106
	-0.46	-1.07	0.40	0.75	0.40
0	78.8	93.3	107.7	115.3	121.2
	0.208	0.104	0.000	0.039	0.071
	-0.83	-0.94	0.00	0.88	-0.18
-1	73.2	87.1	100.4	108.7	112.7
	0.318	0.225	0.147	0.122	0.141
	-0.69	-1.01	-0.73	-0.40	-0.33
-2	69.1	81.5	94.3	101.4	106.7
	0.402	0.339	0.281	0.266	0.257
	-0.82	-0.91	-0.58	-0.59	-0.42

GRID 2

ΔT (°C)	ΔP (%) -80	-40	0	40	80
6	10.5	36.3	85.0	120.2	134.8
	1.676	0.719	0.354	0.305	0.463
	1.75	0.51	0.19	0.24	1.07
3	14.1	45.7	100.5	129.4	142.9
	1.452	0.536	0.192	0.206	0.304
	1.45	-0.01	0.65	0.36	0.68
0	16.6	51.3	107.7	132.5	145.0
	1.408	0.480	0.000	0.109	0.223
	1.55	-0.48	0.00	0.09	0.48
-3	14.8	48.2	85.8	102.8	110.7
	1.606	0.581	0.417	0.403	0.412
	1.97	-0.30	-0.48	-0.29	0.33
-6	12.9	28.3	52.5	62.4	70.8
	1.800	1.144	0.915	0.896	0.889
	2.54	0.64	0.38	0.48	0.58

Table D-1.6

WINTER WHEAT: *Master Yield Grids*

ARGENTINA

GRID 1

	ΔP (%)				
ΔT (°C)	-20	-10	0	10	20
2	70.4	82.7	93.9	100.2	106.7
	0.244	0.147	0.106	0.096	0.120
	-0.31	0.67	1.00	1.54	0.64
1	76.9	88.2	99.2	106.0	111.3
	0.195	0.102	0.053	0.057	0.083
	-0.96	0.17	0.72	1.17	0.54
0	82.5	95.6	104.5	112.0	117.2
	0.158	0.090	0.000	0.050	0.074
	-1.35	1.85	0.00	0.52	0.11
-1	88.0	98.5	108.1	114.5	117.8
	0.144	0.132	0.094	0.076	0.101
	0.39	2.62	3.49	1.52	0.09
-2	89.7	97.1	110.6	116.2	119.3
	0.175	0.163	0.189	0.147	0.161
	2.25	2.74	3.33	1.75	0.44

GRID 2

	ΔP (%)				
	-80	-40	0	40	80
6	10.0	32.3	64.0	85.3	87.5
	2.393	0.860	0.457	0.395	0.562
	2.92	0.99	0.90	0.70	1.00
3	14.2	45.8	82.2	101.6	102.1
	1.763	0.603	0.274	0.239	0.415
	2.42	0.21	-0.49	0.57	0.92
0	17.3	58.5	104.5	114.6	108.8
	1.465	0.398	0.000	0.198	0.367
	1.89	-0.39	0.00	-0.10	0.61
-3	19.3	62.5	104.4	111.9	102.3
	1.275	0.320	0.364	0.278	0.410
	1.53	-0.40	1.91	0.16	0.72
-6	18.8	61.8	96.2	100.5	91.4
	1.221	0.396	0.519	0.363	0.503
	1.49	-0.16	2.56	0.25	0.82

AUSTRALIA

GRID 1

	ΔP (%)				
ΔT (°C)	-20	-10	0	10	20
2	66.9	76.7	88.2	97.4	106.2
	0.289	0.204	0.163	0.114	0.125
	-0.92	-1.23	-1.95	-1.90	-0.75
1	72.3	85.5	97.9	107.1	114.7
	0.231	0.143	0.094	0.070	0.088
	-1.31	-1.32	-3.82	-1.11	-0.68
0	79.1	93.1	106.4	115.8	123.6
	0.171	0.075	0.000	0.043	0.067
	-1.83	-0.90	0.00	1.13	0.11
-1	83.0	95.6	110.2	119.4	127.6
	0.143	0.074	0.043	0.074	0.095
	-2.46	-0.93	-0.72	-0.62	-0.92
-2	84.0	97.1	112.2	120.7	130.9
	0.143	0.102	0.094	0.114	0.145
	-1.71	0.26	-0.15	-0.33	-0.61

GRID 2

	ΔP (%)				
	-80	-40	0	40	80
6	8.0	25.0	50.9	94.8	120.7
	1.809	0.849	0.546	0.298	0.327
	1.88	0.78	0.27	-0.85	-0.56
3	11.7	38.3	74.6	115.7	137.5
	1.434	0.568	0.278	0.154	0.210
	1.59	0.28	-0.58	-1.39	-0.46
0	16.6	53.4	106.4	136.5	155.9
	1.193	0.362	0.000	0.123	0.162
	0.96	-0.30	0.00	-0.74	-1.47
-3	20.2	59.2	110.0	138.5	154.9
	0.988	0.387	0.219	0.200	0.234
	0.53	-0.51	-0.71	-0.60	0.19
-6	19.7	56.5	97.4	128.9	153.2
	1.092	0.469	0.319	0.295	0.359
	1.15	-0.38	-0.31	0.11	0.65

Table D-1.7

WINTER WHEAT: *Master Yield Grids*

INDIA

GRID 1

	ΔP (%)				
ΔT (°C)	-20	-10	0	10	20
	71.0	77.6	87.8	95.0	98.9
2	0.291	0.227	0.163	0.187	0.226
	-0.74	-0.81	-1.07	-0.11	0.03
	78.4	85.9	95.2	102.5	104.3
1	0.222	0.162	0.098	0.120	0.178
	-0.71	-1.34	-1.61	0.82	0.78
	87.0	94.9	103.9	109.6	113.4
0	0.167	0.089	0.000	0.089	0.147
	-0.48	-0.79	0.00	2.08	0.89
	89.9	100.5	108.9	112.6	116.3
-1	0.219	0.106	0.063	0.087	0.143
	-0.46	0.17	0.63	2.78	1.38
	93.8	101.8	112.4	117.2	120.4
-2	0.241	0.174	0.111	0.122	0.153
	0.28	0.15	0.55	0.67	1.02

GRID 2

	ΔP (%)				
ΔT (°C)	-80	-40	0	40	80
	19.6	33.3	49.7	62.2	68.0
6	1.023	0.703	0.568	0.659	0.767
	0.92	0.55	-0.12	0.01	0.43
	30.7	54.3	75.5	87.2	93.5
3	0.940	0.430	0.275	0.377	0.461
	0.65	-0.52	-0.73	-0.04	0.11
	43.1	73.8	103.9	116.4	120.6
0	0.925	0.322	0.000	0.229	0.344
	0.92	0.16	0.00	0.18	-0.07
	54.5	88.6	117.8	126.6	129.0
-3	0.920	0.357	0.177	0.216	0.330
	1.19	1.01	0.65	0.99	0.42
	59.0	96.5	124.6	127.6	125.8
-6	1.055	0.454	0.325	0.362	0.445
	1.63	1.53	0.47	0.01	0.24

PRC

GRID 1

	ΔP (%)				
ΔT (°C)	-20	-10	0	10	20
	74.0	85.3	101.6	111.0	116.7
2	0.176	0.117	0.101	0.114	0.176
	0.27	0.12	-0.04	-0.21	-0.10
	79.2	92.2	104.2	113.0	118.7
1	0.145	0.057	0.054	0.075	0.112
	-0.69	0.34	-0.68	-0.67	-0.59
	82.2	93.8	106.1	113.2	118.9
0	0.192	0.083	0.000	0.040	0.087
	0.29	0.94	0.00	-0.74	-0.89
	81.9	92.5	100.8	105.9	111.0
-1	0.234	0.125	0.081	0.083	0.100
	0.32	1.09	0.18	0.38	-0.39
	79.4	88.6	95.3	100.6	104.3
-2	0.307	0.232	0.160	0.150	0.166
	0.44	-0.26	0.08	-0.17	-0.46

GRID 2

	ΔP (%)				
ΔT (°C)	-80	-40	0	40	80
	15.0	48.1	94.0	133.5	141.5
6	1.218	0.400	0.304	0.382	0.408
	1.75	0.22	1.08	0.08	-0.37
	21.0	56.7	99.2	131.0	144.4
3	0.980	0.328	0.141	0.228	0.341
	1.34	0.15	0.15	-0.40	-0.77
	25.9	63.3	106.1	128.7	141.4
0	0.990	0.376	0.000	0.147	0.270
	1.02	0.07	0.00	-1.01	-1.71
	27.9	61.5	85.8	105.8	113.6
-3	1.016	0.482	0.295	0.307	0.392
	0.67	-0.08	-0.43	0.19	-0.13
	25.0	50.7	66.6	82.1	91.1
-6	1.191	0.733	0.621	0.664	0.691
	0.93	0.04	-0.09	0.23	0.15

Table D-1.8

WINTER WHEAT: *Master Yield Grids*

U.S.

GRID 1

	ΔP (%)				
ΔT (°C)	-20	-10	0	10	20
2	72.8 0.246 -0.87	84.0 0.128 -0.54	95.2 0.072 -0.96	101.7 0.104 1.17	106.9 0.139 1.43
1	78.1 0.209 -1.04	88.6 0.094 -0.43	99.7 0.045 0.50	107.3 0.076 1.59	112.5 0.130 1.45
0	82.5 0.183 -1.23	93.3 0.068 -0.58	102.7 0.000 0.00	111.5 0.074 1.29	118.2 0.127 1.23
-1	83.6 0.209 -1.47	94.1 0.110 -1.50	104.1 0.042 -0.38	111.3 0.069 -0.01	118.4 0.104 -0.10
-2	83.1 0.238 -1.52	93.6 0.155 -1.45	103.8 0.085 -0.16	111.8 0.094 0.24	115.3 0.110 0.38

GRID 2

	ΔP (%)				
ΔT (°C)	-80	-40	0	40	80
6	15.2 1.464 1.80	44.9 0.539 -0.04	71.0 0.272 -0.69	90.7 0.241 -0.05	94.1 0.323 0.34
3	19.6 1.257 1.46	61.1 0.390 -1.03	89.5 0.118 -0.64	110.4 0.179 0.92	111.6 0.319 1.45
0	24.9 1.098 0.95	67.8 0.342 -1.05	102.7 0.000 0.00	126.1 0.188 0.93	124.4 0.299 0.39
-3	27.6 0.992 0.77	70.7 0.367 -0.97	100.1 0.137 -0.51	117.5 0.211 0.63	115.4 0.333 -0.02
-6	28.5 1.018 0.60	63.6 0.585 -0.18	84.8 0.439 -0.88	96.8 0.486 -0.15	95.9 0.553 0.13

USSR

GRID 1

	ΔP (%)				
ΔT (°C)	-20	-10	0	10	20
2	80.1 0.201 -0.44	90.8 0.147 -0.22	103.6 0.123 0.86	111.7 0.146 2.09	117.8 0.193 2.82
1	81.6 0.186 -0.72	93.5 0.104 -0.79	106.2 0.066 1.22	113.7 0.127 2.99	118.1 0.141 2.62
0	83.2 0.182 -1.23	95.9 0.068 -0.66	107.5 0.000 0.00	112.4 0.040 -0.21	116.9 0.068 -0.32
-1	78.7 0.280 -1.28	90.2 0.176 -1.70	100.1 0.120 -1.73	107.2 0.119 -0.77	111.1 0.124 0.07
-2	73.9 0.378 -1.16	81.9 0.308 -1.15	90.7 0.254 -1.20	98.4 0.235 -0.85	103.1 0.231 -0.32

GRID 2

	ΔP (%)				
ΔT (°C)	-80	-40	0	40	80
6	16.6 1.083 0.90	50.4 0.440 -0.36	93.9 0.280 0.44	114.0 0.405 3.15	122.6 0.533 3.52
3	19.8 0.996 0.50	59.3 0.287 -1.27	103.5 0.139 1.67	121.6 0.266 3.15	129.8 0.331 2.95
0	22.6 0.972 0.53	64.7 0.235 -0.83	107.5 0.000 0.00	122.7 0.103 0.61	130.8 0.211 0.55
-3	19.9 1.213 0.97	54.6 0.553 -0.93	79.2 0.441 -1.08	94.7 0.421 -0.90	102.9 0.454 -0.44
-6	16.3 1.196 0.84	39.7 0.698 -0.37	58.9 0.692 -0.27	74.5 0.681 0.12	84.8 0.682 0.11

APPENDIX D–2

PANELISTS' COMMENTS ON THE WEATHER-YIELD QUESTIONS

The agriculture panelists were invited to make explanatory or qualifying remarks concerning their numerical estimates of yield as a function of annual crop weather (see Appendix A-1). Most of the remarks and references—edited and assembled in crop-country order—appear below, whether or not the accompanying estimates were put in the data bases. The respondents' self-ratings of expertise on the 4-3-2-1 scale are shown in parentheses. The yield estimates were made in late 1977 and early 1978, based on the prevailing agricultural technologies of 1976.

Several comments, e.g., Nos. 3, 8, 9, 11, 14 under Argentine corn, apply to more than one crop and country. As in Appendix B-3, we quote panelists who rated themselves "Unfamiliar" with a country-crop combination; however, these panelists' yield estimates were excluded from the Master Yield Grids of Appendix D-1.

CORN

Argentine Corn

1. An ideal seasonal climate for the Argentine corn belt would be current temperatures with the long, 250-day growing season and 50 percent more rainfall over the corn-producing area with the rainfall maximum coming in summers. The production area is too small to compensate for large shifts in climate. (4)

2. The climate of the Argentine corn region has temperatures for the optimum range of corn with marginal water; the effect of natural fertility greatly influences the crop behavior. A slight increase in temperature with a slight increase in precipitation may be the limit in potential yields. (3)

3. Applies to most of the country-crop combinations: countries are large enough that, with major climate change, cropping areas will have major shifts from geographical areas now used. This would give less change than if crop were restricted to present area. (3)

4. Corn in general has a broad range of temperature adaptation and, with lower or higher temperatures, different varieties would be chosen by farmers. Water is the major cause of yield variation. (3)

5. Temperature is moderate and corn could stand changes. Precipitation is variable and to go lower would be disaster. (3)

6. Since neither temperature nor rainfall is limiting Argentine corn production at the present time, I have indicated no increase or decrease in production due to climatic changes except at the low precipitation extreme. (3)

7. I tried to take into consideration the present climate, but mostly guesses! (3)

8. Based on the assumption that November-through-January rainfall is critical. Grid 2 estimates have a very low confidence. In a sense the Grid 2 estimates are "not fair." There is no way that a production area can experience climatic changes of this magnitude and still remain a region for production of the same commodity. If Argentina experienced 40- to 80-percent changes in precipitation and/or 3° to 6°C temperature changes, the same areas would no longer produce corn. The same remark applies to all Grid 2 estimates and will not be repeated. (2)

9. I know of no "good" Argentine corn models. My estimates are analogies from U.S. corn. I have little knowledge about the ultimate limits of yield, and have not marked it. One qualification that could be stated for each country, but will be confined to here is: yield increases for most countries (United States, too!) to 2000 AD will be dependent on having the capital to purchase the more energy-intensive techniques. Capital shortages due to high-priced energy may reduce the rate of expected yield increases.

The numbers in Grid 1 can come from historical experience; that is, yearly fluctuations observed during the past decades will help in making the entries. Grid 2 corresponds to huge crop-weather fluctuations, and knowledge of crop response to these changes can rarely be found in the records of the past few years. Instead, the knowledge must come from experience with controlled conditions, experimental plots, etc. I know very little about such things and therefore my contribution is mainly to Grid 1 and much less to Grid 2. (2)

10. Current temperature is favorable but precipitation is limiting. (2)

11. The temperature/precipitation change "for the whole" season is not as good a way to talk about climate change, as compared to changes during certain critical times during the season. (2)

12. Cooler temperatures can result in delayed phasic development, allowing for longer periods of growth and consequently greater yields if water is not limiting. (2)

13. Thompson's corn model was applied to Grids 1 and 2. The envelope in Grid 3 is for a 50-percent yield. Below that, I feel harvests will not be made. (1)

14. I feel extremely uncomfortable with this part. *If* climate changes take place in the order of Grid 1, the time frame must be specified. If the changes occur in the order of 50–100 years, I think the effect on production would be slight. The range of climate change proposed in Grid 2 would so completely change the agriculture of the region that the estimates are meaningless. My perception is that the most important changes will be shifts north or south or east or west in the geographical location of major production areas. This can, of course, influence production. For example, the "new" corn belt might lie in a more potentially productive soil area. On the other hand, if the optimum climate were centered on a highly populated region, extreme stress socially, politically and agriculturally may result. (1)

U.S. Corn

1. Grid 2 generally out of range except for occasional year for specific areas. (4)

2. Applies to all country-crop combinations: the question of whether changes occur within a season or not could be important for all situations. Must assume it is uniform for this study, but it may not be. (4)

3. Small temperature changes would have no effect on yield. Excess rainfall would hamper planting and harvest, especially in a short, cool season. (4)

4. The U.S. corn crop is not very sensitive to small changes in climate. I have considerable computer simulation research tc back up this statement. With a change in climate, it can shift in any direction. (4)

5. Source: Impact of Climatic Changes on the Biosphere: Part 2, CIAP Monograph 5, DOT-TST-75-85, 1975. (4)

6. I used aspects of a corn-growth model of Splinter to help generate the temperature aspects of the tables. His sensitivity analysis showed an approximate 7-percent change in ear weight for a 10-percent change in temperature. I did not, however, run the model to generate the numbers. (4)

7. June-August rainfall critical. At −3° to −6° C temperature change, northern corn belt would have too short a growing season for profitable production. (3)

8. Individual periods in corn growth require cool/wet or warm/dry weather (the former at mid-season, the latter during germination and harvest). Thus, to speak of the effect of a weather regime for the whole season averages out the different responses. Although cooler weather is generally beneficial, this is mitigated by an increased danger of frost damage and a tendency to use shorter-season, lower-yielding hybrids. Of course, any prolonged climatic change would tend to dislodge corn from its fertile soils. The estimates are based on my research and that of Runge, Thompson and Leeper. (3)

9. Temperature is favorable overall—too warm in south and less than optimum in northern states. Precipitation is favorable—limiting in west. (3)

10. Grid 3: it can get too wet to plant and harvest. (3)

11. Thompson's corn model was used for Grids 1 and 2. (2)

12. I don't feel comfortable with Part II. Distribution of both temperature and precipitation are often much more important than absolute amounts. (1)

RICE

Indian Rice

1. The Part II questions, where the crop-yield responses are to be estimated for selected precipitation and temperature changes, are rather complex problems as far as the Indian situation is concerned. This is because of the fact that there are few areas in the world parallel to India where wheat and rice crops are grown under such a man-modified environment. The bulk of both the rice and wheat crops in India is grown in areas of assured irrigation. Temperature conditions in India are such that they have never been a limiting factor in Indian agriculture. Under these conditions, crop-weather relationship studies in India have remained as a neglected aspect of Indian research; consequently, little is available in the literature to show the impact of climate on the yield of rice and wheat in India. The Division of Agrometeorology, Indian Meteorological Department, Poona, is conducting studies on the estimation of crop yields with weather parameters for the various crops in the states of India.

I tried to work out the relationships for this study. I collected yield data for both crops for a number of years for all the states of India, which have quite diverse climates. Corresponding data pertaining to the rainfall and temperature were also collected. Various statistical techniques and graphical methods were used to establish the matrices showing the relative changes in crop yield corresponding to specific changes in rainfall and temperature. The results arrived at do not seem to be very realistic. I have filled out the grids for the wheat crop, but not for the rice crop.

Rice in India is produced under a highly artificial environment; hence, for the country as a whole it is difficult to establish trustworthy matrices to show the yield response of the crop with variations in rainfall and temperature. The facts given below may clarify the above statement. In the country as a whole, 40 percent of the rice crop area is irrigated. However, in four states of peninsular India, i.e., Andhra Pradesh, Karnataka, Tamil Nadu and Kerala, 77 percent of the crop is produced with irrigation. In the three northwestern states of the country, i.e., Haryana, Punjab and Jammu and Kashmir, 90 percent of the rice crop is produced with irrigation. Collectively, all these states produce 36 percent of India's rice crop. Eighty percent of the rice area in these states is irrigated. In the other major rice-producing areas of the country, 25 to 33 percent of the rice crop is produced with irrigation. Under these peculiar circumstances, the matrices of yield response to variations in rainfall and temperature for the country as a whole which were arrived at were vague, hence I have not filled them out. (No expertise indicated)

2. India's rice population is not very sensitive to climatic change, except from increased variability. The production areas are rather diverse and irrigation is likely to cover 75 percent of the acreage by 1990; the projection is based on this line of reasoning. (3)

3. Excess water has no value and probably does little harm. (2)

4. In the case of Indian rice, temperatures have little effect, even considering changes of up to 5 degrees. India is in the Asian monsoonic region. More than 80 percent of the rice-growing areas are under rainfall farming. Temperature fluctuations in India are small on both diurnal and monthly time scales. Analyses made by Das and others show that precipitation and radiation are the important meteorological variables in their regression models on rice yield. (2)

5. Estimates are in red because I have no references concerning rice models. My "blind" estimates are based on the high compensation point for rice, thereby preferring warmer temperatures, and the requirement for an adequate supply of water. (1)

6. I find this assessment very difficult to make because of my unfamiliarity with Indian agriculture. The success (and failure) depends on the dependability of the monsoon. A production function should be more linked to this than total precipitation. (1)

7. The estimates I made were based on the CIAP of DOP report, 1975. (1)

8. Much (40 percent) irrigated. Small changes in precipitation would have little effect on the water supply. Improved water-use efficiency could offset this. Information now available. (1)

9. Increased rain could be a problem in monsoon period, but would help during dry period. Temperature effects are probably medial with the varieties adapted to general mean. (1)

10. Source: Impact of Climatic Changes on the Biosphere; Part 2, CIAP Monograph 5, DOT-TST-75-85, 1975. (1)

PRC Rice

1. Rice yield-modeling research indicates that the main meteorological factors affecting rice yields in China and Japan are temperature and radiation. Precipitation plays very little role due to irrigation. This does not, however, indicate that precipitation is not important in rice production. On the contrary, rice growing requires more moisture than most other crops. To estimate the effect of precipitation on the rice yield in an irrigated area is very difficult. Such an estimate involves: river flow; water storage in reservoirs, ponds, ditches and snow pack; and the relationship of precipitation to these factors. No attempt is made herein to solve this problem. The following answer to the rice-yield questions regarding the People's Republic of China is restricted only to the temperature effect. Because of extensive irrigation of PRC rice, changes in precipitation would not have a significant effect. (3)

2. The PRC rice crop is grown over a diverse climatic area from subtropical to warm, temperate and from sub-humid to pre-humid. Rice production could be increased by slight warming plus a moderate increase in precipitation plus the limitation of the 20 to 25-year drought in northern and inland China. (3)

3. Any drastic lowering in temperature would eliminate much northern rice culture. (2)

4. Estimates are in red because I have no model on which to base judgments. For logic, see Indian rice, Comment No. 5. (1)

5. Low confidence in the results. Somehow, the onset of the summer rains must be the critical issue for rice production in eastern Asia. (1)

6. The estimates I made were based on the 1975 CIAP report. I am unaware of any good work on PRC rice climate-yield relationships. See: Rice and Weather; World Meteorological Organization Tech Note 144, WMO No. 423. (1)

7. I have trouble with this one. The information packet calls the rice region "hot, humid southern part." The table of mean monthly temperatures doesn't look hot and evidently represents the more moderate highlands. Probably, temperature change would help some places and hurt others. Same for precipitation. (1)

SOYBEANS

Brazilian Soybeans

1. Soybeans would respond greatly to increased soil moisture and increased temperatures, but increased temperature (+6°) above present would reduce yields. (4)

2. For the existing and projected soybean-growing areas in Brazil, the climate is near the ideal. (4)

3. Based on the assumption that the December, January and February precipitation are the most important climatic elements. (3)

4. Temperature and precipitation are favorable. (3)

5. Pattern would be similar to that for U.S. soybeans. Their rain is high and thus the envelope in Grid 3 is tight. (2)

6. Grid 2 is out of range and reason. (2)

7. Thompson's soybean model was applied. Figures are not highly reliable. (1)

U.S. Soybeans

1. Temperature—favorable. Precipitation—often limiting. (4)

2. Soybeans are not affected by temperature within a wide range, although varieties might need to be changed. Yield is reduced a little by loss of water. (4)

3. Soybeans can be and are grown over such a diverse climatic area that any small change in climate would have little or no affect. (4)

4. Source: Impact of Climatic Changes on the Biosphere; Part 2, CIAP Monograph 5, DOT-TST-75-85, 1975. (4)

5. June-August rainfall is critical for production. At −3° to −6°C temperature decrease, the growing season will become too short in the northern areas for soybean production. For soybeans, the temperature decrease would force the area of production south. (3)

6. Moisture is needed for soybeans in July and August. However, they recover quite well from dry spells. Cooling would be generally helpful but would increase frost damage in Minnesota, Iowa and Ohio. My estimates are from a combination of my research, Curry's SOYMOD results, and Thompson's regressions. (3)

7. Beans have been so closely bred for prevailing conditions that any change in environment will simply cause a shift to another variety. (Grid entries assume single variety.) (3)

8. Don't know enough to fill out Grid 2. (3)

SPRING WHEAT

Canadian Wheat

1. The impact of signficant changes in the temperature climate cannot be examined satisfactorily by considering the effects on yields, because lower temperatures, for example, may reduce national production of a crop by reducing the chances of maturing the crop and the extent of the area in which the crop can be grown successfully, without necessarily reducing yield per unit area within the remaining crop-maturing zone (p. 12 of ref. a and p. 93 of ref. b).

I have estimated that a 1°C temperature drop would reduce the area of Canada that is suitable from both a climatic and a soil-geomorphic standpoint for maturing wheat by one third. (The corresponding reduction for barley would be one seventh.) In view of this I am attaching two versions of the Part II grids: one shows my suggestions about the effect of precipitation changes on *yields,* the other shows my suggestions about the effect of both precipitation and temperature changes on Canadian wheat *production.*

For the latter (which is an extension of Table 4, p. 98, ref. b), I have assumed that the lowering of the temperature would reduce the area without affecting yield per acre within the remaining maturing zone. (Perhaps within this remaining zone yields would rise, however, partially compensating for the area reduction, because the cooler temperatures would reduce moisture stresses. An interesting research project would be to analyze each of the 50 or so Canadian prairie crop districts to see how temperature changes might affect both the chances of maturing wheat and the yields, where it would mature.) In Grid 1 I filled out the central axes first and then generated the other entries by multiplying pairs of axial entries. I haven't bothered with this multiplication in Grid 2, and anyway I think Grid 2 implies such radical changes, particularly for temperature, that I wouldn't have much confidence in my extrapolations unless I could do a thorough study of wheat-climate relations under very different conditions than those that have so far been experienced in Canada.

It should be noted that the results for Canadian wheat *production* in response to temperature change are unlike those for wheat *yield* changes calculated for the Great Plains and midwestern areas of the U.S. by Thompson's model (ref. c). (4)
References:

(a) *Impact of Climate Fluctuation on Major North American Food Crops;* published by the Institute of Ecology, Washington, D.C., and the Charles F. Kettering Foundation, Dayton, Ohio.

(b) Williams, G. D. V. An Assessment of the Impact of Some Hypothetical Climatic Changes on Cereal Production in Western Canada; in *World Food Supply in Changing Climate,* 1975 (Proceedings Sterling Forest, N.Y., Conference, December 2–5, 1974).

(c) Impacts of Climate Change on the Biosphere; CIAP Monograph 5, Part 2, Chapter 4.

2. Any cooling of the weather in Canada will dramatically decrease the length of the growing season, thus shortening the yields; large decreases in precipitation with cooling will limit yields from increased cloudiness. (4)

3. Yield increases from lower temperatures are limited by the fact that this would also induce a shorter season and much of the crop would not mature. Increased yields from added rainfall are partially a function of timeliness of added rainfall. If an 80-percent increase comes by doubling the frequency of rainy periods over that for a 40-percent increase, then little, if any, yield increase (over the 40-percent case) may result. (4)

References: Response of Winter and Spring Wheat Grain Yields to Meteorological Variation, Feb. 1977; Planting Date and Wheat Yield Models, Sep. 1977; both by A. M. Feyerherm, Dept. of Statistics, Kansas State Univ. (*Editor's note:* These references were cited for all nine wheat crops.)

4. As indicated, small temperature decreases would actually lead to increased yields (for the area in which growing wheat was still possible). However, temperature decreases would lead to decreased areas in which it would be possible to grow wheat. This decrease in acreage would cause a decrease in overall production. Canada does not have other areas in which to expand wheat acreage in the event of cooling, especially since acreage is concentrated along the southern border with the U.S. (4)

5. For Canadian wheat, 5° C warmer and 100 percent more annual precipitation is required for ideal production, remembering it is a grassland distribution. More than a 100-percent increase in precipitation would likely cause grain losses at planting and harvesting time. (4)

6. Temperature lower than optimum. Precipitation very limited. (3)

7. Warmer temperatures would increase the chances of success in crop establishment at planting. (3)

8. Based on operational models utilized in NASA's Large Area Crop Inventory Experiment (LACIE). (3)

9. With an increase in temperature and moisture, the Canadian wheat crop would shift from a spring to a winter crop, and production would increase. With a decrease in temperature, frosts before maturing would seriously reduce wheat yields. The precipitation in the Canadian wheat belt is minimal, and with any decrease the reduction in yields would be severe, especially with a concurrent increase in temperature. (3)

10. Pitter's wheat model was applied. The trends at lower temperatures will be greatly compensated by a shorter growing season. (2)

11. Based on assumption that June-August precipitation is critical for yields. A −3° and −6° C departure in temperature should reduce the length of the growing season to the point of reducing and/or limiting production. (2)

12. The main wheat region, Saskatchewan, uniformly responds positively to cool weather in June and July and adequate soil moisture in June. (This is the same response that one expects from U.S. spring wheat). But when one is uniformly decreasing all temperatures of the growing season, the length of the growing season will offset the added yield due to the cool June. Thus in Grid 1 cooling has no net effect, but warming will drastically affect Saskatchewan's sensitive June period. Added precipitation is generally helpful. (2) References: (a) Lehane, J. J., and Staple, W. J. Influence of Soil Texture, Depth of Soil Moisture Storage, and Rainfall Distribution on Wheat Yields in Southwestern Saskatchewan; *Canadian J. of Soil Science,* 42 (1965), pp. 207–219; (b) Williams, G. D. V. Estimates of Prairie Provincial Wheat Yields Based on Precipitation and Potential Evapotranspiration; *Canadian J. of Plant Science,* 53 (1973), pp. 17–30.

13. Grid 2 is out of range. (3)

14. If warm enough temperature, could grow some winter wheat. Much warmer and wetter could have replacement of acreage with early corn and soybean varieties. (2)

15. Source: Impact of Climatic Changes on the Biosphere; CIAP Monograph 5, Part 2, DOT-TST-75-85, 1975. (2)

U.S. Spring Wheat

1. Rather than use aggregated models, consideration for the temperature and precipitation patterns in the U.S. was taken to yield estimates of changes. As climate changes, producing regions will probably also change to minimize effects. Such is reflected herein. (4)

2. U.S. spring wheat generally could benefit from increased moisture from preseason to July. Evapotranspiration has been shown to have a high negative correlation with yield—particularly in June. Warm Aprils are beneficial, but this gain is overridden by the damage of hot days around heading. Prolonged and significant warming would, of course, push spring wheat acreage into Canada. (4)

3. Spring wheat responds to temperature and moisture and if temperatures increase, yield would naturally increase. Precipitation increases would dramatically cause yield to stabilize. (4)

4. Increases in precipitation per storm would increase yields, but increases due to increased frequency would not have the same beneficial effect. Decreased temperatures would be beneficial up to the point where the season becomes too short for the crop to mature. (4) References: see Canadian wheat, Comment No. 3.

5. Estimates were calculated using the linear-additive model described in IES Report 49: A Detailed Model of the Production and Consumption of Spring Wheat in the United States; Institute for Environmental Studies, University of Wisconsin, Madison, 1975. Values for the row −6°C were subjectively lowered because this temperature departure would place the planting month (April) mean temperature near 0°C, implying delays of at least one month, and severely inhibited germination. The possibility of late frosts is high with crop failures as a consequence. For the remaining scenarios, I assumed that each month of the growing season departed from its mean temperature by the *same* number of degrees and the *same* percent of total precipitation, which is not terribly realistic. (4)

6. U.S. spring wheat will be rather sensitive to any climatic shift but not as sensitive as the Canadian crop. The crop yields are very sensitive to increased climatic variability. (4)

7. These results represent the average of computations using three spring wheat models evaluated during NASA's Large Area Crop Inventory Experiment. These models are in remarkable agreement over Grid 1. Over Grid 2 the subject space of the dependent [sic] variables used in model development is exceeded and results are unreliable. Significant geographical shifts in planting would undoubtedly take place well within Grid 1. (4)

8. For North Dakota I used Thompson's model. (4) Reference: Ramirez, J. M., Sakamoto, C. M., and Jenson, R. E. Impacts of Climatic Change on the Biosphere; CIAP Monograph 5, Part 2—Climatic Effect, Dept. of Transportation, September 1975.

9. Present varieties are well adapted to weather conditions. Wheat response is centered on those conditions. (3)

10. Based on assumption that May-August rainfall is the critical climatic element. At a −3° to −6°C temperature change, the northern areas would have too short a growing season. (2)

11. Temperature—warmer than optimum. Precipitation—less than optimum, usually limiting. (2)

12. The same grids as for Canada. Don't know enough to be any more specific. Winter hardiness may lead to more acreage in winter wheat vs. spring wheat. (2)

13. Rising temperatures would cause substitution of winter wheat for spring wheat. (2)

14. Source: see Canadian wheat, Comment No. 15. (2)

USSR Spring Wheat

1. The region would be benefited by added precipitation and lower temperatures during June and July. However, as temperatures decreased, more and more of the region would have non-maturing wheat and overall yields would decrease. (4) References: see Canadian wheat, Comment No. 3.

2. As indicated, small temperature decreases would actually lead to increased yields for the area in which growing wheat was still possible. In the event of cooling, some winter wheat acreage could be converted to spring wheat which could make up for at least some of the spring wheat acreage loss. (4)

3. Reference: Ramirez, J. M., Sakamoto, C. M., and Jensen, R. E. Section 4.1.2, Wheat, Impacts of Climatic Change on the Biosphere; CIAP Monograph 5, Part 2—Climatic Effects. J. Bartholic and R. E. Jensen, Editors. (4)

4. In almost all USSR spring wheat regions, yields would be up due to cooler Junes. Temperature earlier and later in the growing season will evoke mixed responses. The ultimate gain due to cooling is rapidly matched by the increased frost hazard. April through June is a time of general moisture shortage. At other times, the precipitation needs vary with location. Wetter weather generally helps the northern regions the most. The estimates are based on the work of Zabijaka and other sources. (3) References: (a) Kogan, F. M. Estimate of the Summer Wheat Yield by Meteorological Data in Regions With a Clearly Continental Climate; *Meteorol. i Gidrol.,* 10, 1960, pp. 14–18; (b) Bogdanov, T. F. The Dependence of the Spring Wheat Yield on the Amount of Precipitation in the Non-Chernozem Zone; *Meteorol. i Gidrol.,* 7, 1965, pp. 46–48.

5. Probably near borderline on both temperature and precipitation now. (3)

6. USSR spring wheat crop is grown on very marginal lands, particularly east of the Urals. Any change in climate will cause a major shift in national yields. However, the USSR crop is not as sensitive as the Canadian crop because of the vast areas involved. (3)

7. Results are from LACIE operations models and a "universal" wheat yield model developed under NASA contract at Kansas State University. (3)

8. Moisture is the principal factor limiting USSR spring wheat yields; with more snow cover much of the area would switch from spring to winter wheat and yields would be increased. (3)

9. Pitter's wheat model is used, but there will be some negative compensation at lower temperatures due to a shortening of the growing season. Such was not estimated. (2)

10. Temperature—favorable. Precipitation—very unfavorable. (2)

11. Same as for Canadian wheat. Can't be more specific from information shown. (2)

12. May-July precipitation is the most critical. A temperature change of −3° to −6°C should shorten the growing season to the point where production is either reduced or prevented. (1)

13. Probably any decrease in average temperature would require southward movement of the crop. (1)

WINTER WHEAT

Argentine Wheat

1. Wheat is grown in an area of highly variable rainfall and natural fertility; with an increase in rainfall and temperature, lush growth may rapidly deplete available nutrients and a large increase in precipitation may be negated. (4)

2. For winter wheat with rainfall maximum in summer months, 3° cooler and 25 percent more precipitation would be about all that is possible because *more* would make increased harvest loss *very* likely. The production area is too small to compensate for any large shifts in climate. (4)

3. Most of the wheat is grown in the Pampas, a relatively ideal wheat climate. In Entre Rios as well as Santa Fe, cooler temperatures than exist now should be beneficial for wheat. A model for Buenos Aires was used since the major production is from this province, which includes a large portion of the Pampas. (4)

4. Higher precipitation would help. Temperature is at medial point of tolerance now. (3)

5. A single yield model placing greatest weight on Buenos Aires Province was used. The model was taken from those developed for NASA's Large Area Crop Inventory Experiment. Evaluation of the model has shown a lack of adequate response to moisture stress. (3)

6. Both increased precipitation and decreased temperatures are beneficial up to certain levels. We assume responses similar to those for the spring wheat model that we used. (3) References: see Canadian spring wheat, Comment No. 3.

7. Yield circle again encompasses the 50-percent yield mark, approximately. Pitter's wheat model was applied. (2)

8. Assessment based on assumption that October, November and December precipitation is critical. (2)

9. Erratic rainfall in the Pampas will keep yields variable no matter what the mean yield in the different areas. Temperature seems to be the most sensitive aggregate variable. Precipitation does have an effect locally, but over the whole wheat-growing region tends to average out. Growing season, particularly in the north, appears long enough not to be affected by moderate (1° to 2°C) cooling. (2) Reference: The Z-Index and Subitaneous Events as Variables for Estimating Wheat Yield in Argentina; CCEA Tech. Note 76-4, 1976.

10. In the southern hemisphere such as Australia and Argentina, where wheat is seeded in autumn, there is a cooling and then warming as grain filling proceeds. Thus, yields tend to be lower than in summer seedings in the northern hemisphere. Temperature—unfavorable. Precipitation—limiting. (2)

11. Grid 2, here and elsewhere, is completely unrealistic. (2)

12. If weather gets wet enough, could have major shift to corn and soybeans. (2)

13. Wheat, being a "cryophyllous" crop, would benefit most from lower temperatures. Higher mean temperatures would imply less yield. Here though, is the mean raised by higher temperatures in the summer, in the winter, or both? In the daytime, in the nighttime, or both? (1)

14. Source: Impact of Climatic Changes on the Biosphere; CIAP Monograph 5, Part 2, DOT-TST-75-85, 1975. (1)

Australian Wheat

1. With current technology, Australian yields would respond dramatically to increased precipitation, although large increases in precipitation would limit yield due to water-fertility problems. (4)

2. The Australian continental climate is more difficult to judge since it is split between winter Mediterranean type and humid all-season type for annual precipitation distribution. Wheat production is also in an east-west belt on this continent. (4)

3. A model developed for New South Wales was utilized for the analysis. (4) Reference: Sakamoto, C. M. An Index for Estimating Wheat Yield in Australia; Center for Climatic and Environmental Assessment, Technical Note 76-3, Columbia, Missouri, November 1976.

4. Rain increase would hurt the east, help the west. Thus, not much yield increase is possible with increasing rain. Temperature is probably medial for wheat-production range now. (3)

5. Dryness is a major deterrent to high yields, and increased precipitation could be used more beneficially than in the northern hemisphere locations. Cooler temperatures would appear beneficial up to a point, and then the season may be lengthened into warmer periods during heading, resulting in decreased yields. (3) References: see Canadian spring wheat, Comment No. 3.

6. Thompson's wheat model was applied. It probably underestimates the adverse effects of drought. The yields for – 40 and – 80 percent precipitation could be reduced 25 percentage points to accomplish such accounting, and the – 20 percent precipitation values can be reduced 8 percentage points. (2)

7. Based on the assumption that November, December and January precipitation is the most critical. (2)

8. Temperature—higher than optimum. Precipitation—extremely limiting. (2)

9. Grid 2 out of range. (2)

10. The temperature range and amount of precipitation are less important than the distribution of precipitation. (1)

11. Source: see Argentine wheat, Comment No. 14. (1)

12. *Editor's note:* Panelist (Expertise = 1) made no estimate but cited Sakamoto (see Comment No. 3 above) and: Cornish, E. A. The Influence of Rainfall on the Yield of Wheat in Southern Australia; *Australian J. of Scientific Research, Series B, Biological Sciences,* 33 (1959), pp. 178–218.

Indian Wheat

1. Forty-five percent of the wheat area of the country is irrigated. However, in the four northwestern states of the country, i.e., in Punjab, Haryana, Rajasthan and Uttar Pradesh, 76 percent of the wheat crop is irrigated. Collectively, these states produce 68 percent of the wheat of India. Punjab State, which alone contributes about one fifth of the production of the country, has 90 percent of the wheat crop under irrigation. This irrigation is well assured from perennial canals and tube wells. The yield and rainfall data of the previous 10 years show that even during the years when the rainfall during the crop season was almost absent, it hardly affected the crop yield. With this assured supply of irrigation in the major wheat-producing region of India, the matrices established for the country as a whole are shown in the two grids. (*Editor's note:* See also the first two paragraphs of Comment No. 1 under Indian rice; an expertise of 4 was assigned by the project staff.)

2. Wheat is grown in very warm parts of India which are marginal for proper development, and large temperature increases will negate any effect of increasing precipitation. The crop could use more water with the same temperature regime (as evidenced by large increases under irrigation). (4)

3. Increased precipitation during the season would be beneficial in the non-irrigated areas only, but it would be extremely beneficial there. Yields are limited by high temperatures throughout most of the wheat-growing regions. Lowering of temperatures would make the climate more like some of the U.S. winter wheat area. (4) References: see Canadian spring wheat, Comment No. 3.

4. These estimates were adapted from a statewide multiple regression model of yield for India, with individual states aggregated to arrive at national estimates. Because the model covers a large area that includes widely different agronomic practices (e.g., HYV vs. traditional strains) and dramatically different climatic regimes, the model estimates, especially for the extreme climatic cases which lie well beyond the range of observations used in model estimation, must be regarded as nothing more than poorly educated guesses. (4)

5. I feel that climate, particularly water, is the important limiting factor in expanded Indian wheat production in the marginal, arid area of northwestern India. (4)

6. Estimate is based on a regional wheat model developed for the period 1953–75. (4) Reference: Sakamoto, C. M. A Wheat Yield Model for Uttar Pradesh, India; unpublished manuscript, Center for Climatic and Environmental Assessment, NOAA, Columbia, Missouri, 1977.

7. Precipitation is near optimal point of wheat adaptabilities now. Temperature response is medial, too. (3)

8. Real shifts of the general circulation which impact the monsoon rains would have a larger impact than shown by these grids. Three different models were examined. The agreement between models was not good. (3)

9. Additional precipitation during the monsoon would have no effect on Indian wheat yields. Additional precipitation during the wheat-growing period would have little effect on yields except that the additional cloudiness would reduce solar radiation and the higher humidity would increase the disease loss. (3)

10. Michael's and Scheer's model of wheat yields in India was used. It probably underestimates temperature effects or drought conditions. (2)

11. Large yield discrepancies between Bombay and Punjab appear to be correlated with the December-February rainfall. This indicates that moisture at this time is quite beneficial. The cool weather that wheat likes is, however, marginally present. The effect of irrigation is to cut down on the precipitation sensitivity, but the temperature sensitivities should remain constant for the next few years. (2) Reference: Dayal, Ram. Impact of Rainfall on Crop Yield and Acreage; *Indian J. of Ag. Econ.,* 20 (1965).

12. Temperature increases could seriously reduce yields. Precipitation favorable. (2)

13. An increase in mean precipitation would only come in the monsoon period and have little or no affect on the water available for wheat. (2)

14. Large increases in rainfall were estimated to occur during the monsoon. This would produce mostly runoff and be of marginal help to wheat grown in the drier periods of the year. (2)

15. I do not have sufficient knowledge of climate in India to provide very accurate estimates here. Scope for increase can't be as great in India as in temperate climates, as temperatures must be near their optimum now. Any increase in rainfall will likely cause greater losses than at present, as monsoon rains cause flooding, and any decrease will likely cause more widespread droughts. (2)

16. Dependent on cool-season rain. Very low confidence in this assessment. (1)

17. Little confidence in these estimates due to the great variation between the climate regions in which wheat is grown. (1)

PRC Winter Wheat

1. Any decrease in precipitation or temperature would be dramatic in yield effects. (4)

2. Lower rainfall would probably take regions out of wheat production. Lower temperature would shift production to spring wheat. But where *winter* wheat persists, the lowered temperature would cause great decreases in yield. (3)

3. The winter wheat area could benefit by marked increases in precipitation and lower temperatures during the growing season. More and more of the precipitation needs are being satisfied by irrigation; this could result in less year-to-year variation in yields. (3) References: see Canadian spring wheat. Comment No. 3.

4. A warmer and wetter climate in China would shift the wheat production west and north into productive grass and desert lands. (3)

5. Grid 1 same as for Canadian wheat; Grid 2 out of range. (2)

6. A hotter, wetter climate would probably favor leaf diseases. (2)

7. The estimated yields of winter wheat under different temperatures and precipitations were computed using the Center for Climatic and Environmental Assessment winter wheat models with climatic analogues. (2)

8. Analysis is the result of application of a generalized winter wheat weather-yield model developed under NASA contract and a station/country yield model developed by the University of Wisconsin under NOAA contract. The results are at best tentative. (2)

9. Pitter's wheat model was used, but drought conditions were neglected. To compensate, lower the yields for −40 and −80 percent precipitation by 25 percentage points, and the yields for −20 percent by 8 points. (1)

10. April through June should be the critical period for rainfall. Low confidence in these estimates. (1)

11. I am unaware of any good climate-yield work on PRC wheat. (1)

12. Not very familiar with climate in China. Guesses based on some knowledge of crop-climate relationship and based on information given for Chinese wheat regions in the background notes. (1)

U.S. Winter Wheat

1. Rather than use any specific model, consideration for temperature and precipitation patterns is taken, as for spring wheat. (4)

2. Increases in precipitation would help. Temperature is about right for present varieties. (4)

3. Increased precipitation would increase deleterious effects in the eastern part of this region and offset some of the beneficial effects in the west. Lower temperatures would show beneficial effects, possibly down to the −6° C level shown in the table. (4) References: see Canadian spring wheat, Comment No. 3.

4. As with the U.S. spring wheat values (Comment No. 5), these are generated by a linear-additive regression model estimated on 45 years of data. In this set, it would be a very rare event to have the signs of temperature and precipitation departures be the same from planting through harvest. This is a more serious limitation of validity, since the winter wheat season is so much longer than that of spring wheat. Further caution is advised in the interpretation of the extreme cases. (4)

5. The present U.S. winter wheat belt will be sensitive to warmer and drier climatic shifts. Cooler and wetter seasons would favor yield increases in the southern and western areas. (4)

6. Significant changes in planting patterns would probably happen if yields were consistently depressed 25 to 20 percent. (4)

7. Reference: Ramirez, J. M., Sakamoto, C. M., and Jensen, R. E. Wheat in Impacts of Climatic Change on the Biosphere, CIAP Monograph 5, Part 2—Climatic Effects, September 1975. J. Bartholic and R. E. Jensen, Editors. (4)

8. Wheat in most of the Great Plains derives good yields from added precipitation. However, too great an amount will promote lodging and a poor protein content. At least one or two dry weeks are needed for harvest. As usual, wheat responds favorably to cool weather. Wheats in the more eastern regions—Illinois and Indiana—respond differently. They are not nearly as moisture-limited. (3)

9. Winter wheat in the selected states is sensitive to moisture. Drastic temperature increase with more rainfall might induce more disease problems. (3)

10. Rainfall total for April-June is the critical climatic element. A decline of −6°C in mean temperature would make must of the area too cold for winter wheat because of winterkill. The area would then change to spring wheat production. (2)

11. Temperature—favorable. Precipitation—very unfavorable. (2)

12. Don't know enough to fill out Grid 2. (2)

13. Source: See Argentine wheat, Comment No. 14. (2)

USSR Winter Wheat

1. The base yield (34.2 bu/acre) indicates a very favorable climate (wintertime precipitation and cool temperature from jointing to ripe) for winter wheat. Extreme temperature drops for the entire growing season could mean that part of the winter wheat crop would not mature and/or harvesting would run into planting time for the subsequent year. (4) References: see Canadian spring wheat, Comment No. 3.

YIELD COMMENTS

2. Comment No. 2, USSR spring wheat, applies. (4)

3. See USSR spring wheat, Comment No. 7, for basis of estimates. (4)

4. Reference: Sakamoto, C. M. Wheat Yield Models for the U.S.S.R.; Center for Climatic and Environmental Assessment, Technical Note 76-1, Columbia, Missouri, May 1977. (4)

5. General temperature requirements are difficult to specify because of the tendency of USSR winter wheat to winter-kill. Most regions find that warmer temperatures will decrease yields—due to stress sensitivity at heading and grain filling. Adequate soil moisture at all times is crucial for high yields. The eastern regions are particularly benefited by wetter weather. The estimates are based on the work by Zabijaka and other indirect information. (3) References: (1) Zabijaka, V. A. Preliminary Weather-Crop Yield Model for Soviet Grain; Foreign Demand and Competition Division, ERS, USDA; (b) Ulanov, E. S. The Effect of May Precipitation on Yields of Winter Wheat in the Steppe Regions of the Ukraine and Northern Caucasus; *Meteorol. i Gidrol.*, 5, 1966, pp. 17-25.

6. They are marginal on temperature now. Wheat is very tolerant of climatic change close to its ideal mean. (3)

7. USSR winter wheat is produced over a very diverse climatic area, and any change will have offsetting effects in other areas. Therefore, it will be difficult to change USSR winter wheat production with small changes in the climate. (3)

8. Pitter's model was used. There will be some diminution of yields at lower temperatures through shortening of growing season length. (2)

9. Temperature and precipitation favorable. (2)

10. Same as U.S. grids. Can't be more specific. (2)

11. Winter wheat is in a favorable environment, so little changes should have little effect. Large temperature changes in either direction should adversely affect yields. (2)

12. The April-July rainfall is the most critical. The winter wheat production would be curtailed by temperature as cold as a 6° C departure. Winter-killing would shift production to spring wheat. (1)

13. No guesses. Could be like Canada, perhaps. (1)

14. Source: see Argentine wheat, Comment No. 14. (1)

APPENDIX D–3

ANTICIPATING THE RESPONSE OF YIELDS TO CLIMATE CHANGE

INTRODUCTION

What do the annual-yield surfaces of Section 5-5 imply about the response of crops to climate change? There is a natural, graphical approach to this question: the discrete predictive methodology described in Chapter I can be simulated by shifting the BND polygons on Figures V-1 through V-15 and observing the configurations that result. The method is anything but precise, but it can indicate the *directions* of the effects of an assumed climate change on the expected values and standard deviations of annual yields.

CHANGES IN EXPECTED YIELDS

Actually, the effect of a climate change on the expected (or average) yield of a crop can be ascertained without regard to the BND polygon. Simply by plotting an assumed climate change as a point in the $\Delta T,\Delta P$-plane and comparing the relative annual yield at that point with the relative annual yield at the origin, one can usually determine whether the expected value of annual yields would be greater or less than the expected yield in the Base Period. The numerical difference between the two relative annual yields may not, however, provide a good estimate of the difference between the two expected yields.

CHANGES IN THE VARIABILITY OF ANNUAL YIELDS

In some cases one can also perceive qualitative differences in the variability of annual yields between the Base Period and an assumed climate state. Such differences in variability are manifested graphically by the patterns of the yield contour curves which lie inside the BND polygon before and after it is shifted. These patterns, in turn, can be distinguished by two rough criteria: the standard deviation of annual yields will tend to increase or decrease in accordance with increases or decreases in (1) the number of yield contour curves intercepted by the boundary of the BND polygon, and (2) the steepness of the yield surface near the center of the BND polygon, where probabilities are relatively high. In our figures, the local density of the yield contour lines is an index of steepness.

AN EXAMPLE: THE SOVIET WHEAT CROPS IN THE EXTREME CLIMATE SCENARIOS

Soviet spring wheat and winter wheat are instructive if the reader is disposed to experiment with the graphical approach to variability. As noted in Table S-2 of the Summary, climate change affects these crops quite differently with respect to the variability of annual yields. For example, relative to the Base Period and as measured by the coefficient of variability, the variability of Soviet spring wheat decreases by "small" amounts in both the Large Cooling Scenario and the Large Warming Scenario. The variability of Soviet winter wheat, on the other hand, increases by a "large" amount in large cooling and decreases by a "very large" amount in large warming. It can be shown graphically that these disparate variability responses are consistent with the annual-yield response surfaces and BND polygons of the two crops. After converting the pertinent coefficients of variability (Table III-6) to standard deviations, one shifts templates of the respective BND polygons to the two positions which characterize the extreme climate scenarios, and then compares the resulting configurations with the Base-Period configurations according to criteria (1) and (2). (Strictly speaking, the templates should be contracted or expanded in the precipitation dimension according to the assumption about the effect of climate change on the standard deviation of precipitation; this refinement is not necessary for the modest climate changes involved in the present example.)

In the case of Soviet spring wheat, the two graphical criteria are indecisive but still generally consistent with Table S-2. (Although it indicates small differences among the standard deviations of spring wheat yields in the three climate states, the BND-template method is not sharp enough to discriminate with certainty the algebraic signs of the small differences.) The case of Soviet winter wheat, however, is quite clear-cut. Both graphical criteria of variability point unambiguously to standard deviations that agree with Table S-2.

THE ROLE OF THE POSITIVE CORRELATION COEFFICIENT IN THE BEHAVIOR OF SOVIET WINTER WHEAT

Despite its obvious limitations, the graphical approach to variability underscores the anomalous behavior of Soviet winter wheat among the 11 key crops of the higher and lower middle latitudes (see Table S-2). The variability pattern of Soviet winter wheat is even unlike that of its spring-wheat cousin, although both crops have similar yield response surfaces and are subject, in our model, to the same climatic changes. Clearly, the difference in variability between the two Soviet wheat crops is mostly due to the different "shapes" and orientations of their respective BNDs. As explained below, the orientations and (to a lesser extent) the "shapes" of the two BNDs are governed by the correlation between annual temperature and precipitation. In this connection, we note that the BND for Soviet winter wheat has a positive correlation coefficient, while the BNDs for all the other key crops of the mid-latitudes, including Soviet spring wheat, have negative correlation coefficients (see Table V-1).

If a BND function were plotted as a contour map in the temperature-precipitation plane, the curves of constant probability density would form a family of concentric ellipses, each with the same shape (eccentricity) and the same orientation in the plane. In general, the "shape" of the BND, by which we mean the shape of the ellipses, is a function of both the correlation coefficient r and the ratio of the standard deviations of temperature and precipitation, which we denote by p. (The shape is determined solely by r when $p = 1$, and solely by p when $r = 0$.) The orientation of the ellipses is also a function of r and p.

For all our crops, the longer axes of the ellipses lie in the first and third quadrants of the temperature-precipitation plane when r is positive; they lie in the second and fourth quadrants when r is negative. Hence, the sign of the correlation coefficient has a qualitative effect on the orientation of the ellipses. The orientations and shapes of the elliptical BND contour curves are suggested by the BND polygons in Figures V-1 through V-15.

CONCLUSIONS

The graphical method described above offers some insight into the essence of the climate-response model. The Soviet wheat example illustrates how a Base-Period yield distribution is perturbed by the complex interaction of a climate-change vector with the annual-yield function and the BND. In particular, it shows how the orientation of the BND—hence the correlation coefficient—can affect the outcome.

[illegible]

[illegible]

[illegible]

[illegible]

APPENDIX D-4

COMMENTS ON THE SENSITIVITY OF THE MODEL

INTRODUCTION

It was asserted in Section 5-11 that the expected normalized relative yields and NRCVs are quite insensitive to the BND parameters s_T and s_p. Here we give the rationale for the assertion and adduce some further evidence that also casts light on the role of the correlation coefficient. In addition, we consider the effect of relaxing the assumption that recent patterns of annual crop weather would persist in each of the climate scenarios.

INSENSITIVITY OF THE EXPECTED NORMALIZED RELATIVE YIELDS

Our reasoning about the expected yields of a given crop runs as follows. Consider a scale of relative yields, not necessarily normalized.

- Let $\overline{Y}_B$ and $\overline{Y}_X$ denote the expected yields calculated for the Base Period and one of the five climate scenarios ("Scenario X") on the basis of the nominal BND parameters s_T and s_p.
- Consider new BND parameters $^*s_T$ and $^*s_p$ lying within 25% of the nominal values. Using these parameters with the same annual-yield matrix, we calculate new expected yields $^*\overline{Y}_B$ and $^*\overline{Y}_X$ for the Base Period and Scenario X.
- To measure the effects of the new BND parameters on the expected yields we define d_B and d_X by the equations

$$^*\overline{Y}_B = \overline{Y}_B(1 + d_B),$$

$$^*\overline{Y}_X = \overline{Y}_X(1 + d_X).$$

- From the sensitivity analysis in Section 5-10 we know that at most the magnitude of d_B is about 0.02.
- We conjecture that d_X is also small, but more importantly not much different from d_B. The bases for this conjecture are the principle of continuity and the fact that the temperature and precipitation changes associated with Scenario X are rather small.
- Therefore, the ratio of $^*\overline{Y}_X$ to $^*\overline{Y}_B$ should be very nearly equal to the ratio of $\overline{Y}_X$ to $\overline{Y}_B$.

Basically, the argument is that a small climatic shift of two BNDs on the annual-yield matrix should result in nearly equal relative perturbations of their respective Base-Period expected yields, provided their standard-deviation parameters do not differ by more than 25%.

Since the expected *normalized* relative yields in the climate-crop scenarios are ratios of the type just described, it follows that the choice of s_T and s_p (within the 25% criterion) has little effect on them, hence the contention

> C1: For a fixed country-crop combination, the expected normalized relative yields for the respective climate scenarios ought to be quite insensitive to the common values of s_T and s_p used in the scenarios.

An almost immediate consequence is the contention

> C2: In a given climate scenario, the *ratio* of the expected normalized relative yields of two country-crop combinations ought to be comparably insensitive to the values of s_T and s_p used in the Base Period and the scenario, even if *different* parameter changes were applied to the BNDs of the two crops.

INSENSITIVITY OF THE NRCVs

The variability of relative yields is another matter, for 25% changes in s_p have a strong effect on the CV of calculated relative annual yields. Nevertheless, because the NRCV is a ratio like the expected normalized relative yield, the analog of the expected-yield argument leads to similar conclusions about NRCVs relative to a more limited range of s_T and s_p. We would guess that contentions C1 and C2 are valid for NRCVs provided s_T is changed by no more than 25% of its nominal value and s_p by no more than 10%

THE CROP-SEASON BNDs

Although C1 and C2 initially were extrapolations from the Base-Period sensitivity analysis, we later realized that additional evidence was available, namely a discarded set of yield projections. Originally, we had carried out the climate impact assessment using BNDs which were based on crop-season temperature and crop-season precipitation rather than heading-period temperature and crop-year precipitation. Thus, in addition to the controlled 25% excursions on s_T and s_p which apply only to Base-Period yield distributions, we had uncontrolled excursions—not only on s_T and s_p but also on the correlation coefficient—which apply to the five climate scenarios as well as the Base Period.

For the purposes of this discussion we refer to an original crop-season BND as "BND-1" and to the corresponding BND characterized in Table V-1 as "BND-2." The two Chinese crops are the only ones for which BND-1 and BND-2 have the same parameters. Following is a summary of the differences in parameters between BND-1 and BND-2 for the remaining 13 key crops:

- In most cases, the standard deviation of temperature was smaller for BND-1 than for BND-2 because the crop season of the former was longer than the heading period of the latter. For 11 crops the s_T of BND-1 was 8% to 54% smaller than the s_T of BND-2. These differences tended to make the expected yields calculated with BND-1 larger than those associated with BND-2 and to make the CVs of BND-1 smaller than those of BND-2.
- The standard deviation of precipitation generally was larger for BND-1 because the crop season of BND-1 was shorter than the crop year of BND-2. In the case of Brazilian soybeans both BNDs had the same s_p, but for the other 12 crops the s_p of BND-1 was 7% to 106% larger than that of BND-2. These differences tended to make the expected yields and CVs associated with BND-1 smaller and larger, respectively, than those calculated with BND-2.
- The correlation coefficient of BND-1 was usually quite different in magnitude from that of BND-2. In two cases, U.S. and Soviet winter wheat, the coefficients even differed in sign between BND-1 and BND-2.

Thus, relative to BND-2, the s_T and s_p of BND-1 generally have offsetting effects on both the expected yield and the CV of a country-crop combination for a given climate change, but we are uncertain about the effects of the different correlation coefficient used in BND-1. The correlation coefficient affects the "shape" and orientation of a BND in a complicated way (see Appendix D-3). The yields calculated with BND-1 and our experience with moving BND polygons on the annual-yield response surfaces suggest that the shape and orientation of the BND (hence the correlation coefficient) can be important, especially for the projected variability of annual yields.

THE SENSITIVITY CONJECTURES VINDICATED?

We found that the largest difference between an expected normalized relative yield calculated with BND-1 and the corresponding expected yield calculated with BND-2 was 1.06%. Of the 13 × 5 = 65 non-Chinese crop-scenario combinations, for only seven cases did the difference in expected yields exceed one-half percent, and these seven cases were confined to the two extreme climate scenarios.

The NRCVs were less convergent than the expected yields. The spectrum of percentages by which the NRCV for BND-1 differed from the NRCV for BND-2 in the 65 non-Chinese crop-scenario combinations was as follows:

- 0% to 1%: 28 cases.
- 1% to 5%: 28 cases.
- 5% to 10%: 5 cases, of which 4 were in the two extreme climate scenarios.
- Greater than 10%: 4 cases, all of them Soviet winter wheat.

We contend that these data are not necessarily inconsistent with the proposition that NRCVs should be relatively insensitive to moderate changes in s_T and s_p.

SOVIET WINTER WHEAT AND THE ROLE OF THE CORRELATION COEFFICIENT

At first glance, Soviet winter wheat might be cited as a counterexample to our conjecture about NRCVs: in passing from the coolest to the warmest climate scenario, the percentage differences between the NRCVs of BND-1 and BND-2 were −21%, −11%, +7%, +17%, +35%. However, we believe that this glaring exception to the conjectured rule concerning NRCVs is due more to a difference in correlation coefficients than to differences in the standard deviations of temperature and precipitation. For BND-1, the correlation coefficient in the Soviet winter wheat region was −0.55 compared to +0.33 for BND-2.[1] The reversal of signs and the consequent change in the orientation of the BND had a strong effect on the CVs but not on the expected yields, which differed by at most 0.33% between the two BNDs. For both BNDs, the expected yields of Soviet winter wheat increase in the progression from the coolest to the warmest global climate scenario. Under BND-1, the CVs also tended to *increase* with global temperature, but under BND-2 the CVs *decrease*.

Soviet winter wheat does more than break the pattern of congruity between the NRCVs of BND-1 and those of BND-2. As noted in Appendix D-3, the variability of Soviet winter wheat yields is exceptional in the context of BND-2 alone. Whereas the CVs of this crop *decrease* with increasing global temperature and expected yield under BND-2, the CVs of the other three key crops of the northern higher middle latitudes—Canadian, U.S. and Soviet spring wheat—tend to *increase* (see Table III-6). Again we are inclined to attribute the contrary behavior of Soviet winter wheat largely to differences in correlation coefficients: BND-2 for Soviet winter wheat has a positive correlation coefficient while BND-2 for each of the three spring wheat crops has a negative correlation coefficient.

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[1] For BND-1, s_T and s_p were 1.00° C and 17%, respectively. For BND-2 they are 1.38° C and 12%.

IMPLICATIONS OF THE CROP-SEASON BNDs

The calculations with BND-1 do not settle the question about the sensitivity of the yield distributions to changes in the BND parameters. They suggest, however, that "correct" values of s_T and s_p may be less important for NRCV calculations than a "correct" value of the correlation coefficient. Therefore, any future investigation of the sensitivity question should include controlled experimentation with the correlation as well as the standard deviations of temperature and precipitation. Also, it would be desirable to interrogate climatologists about the likely effects of climate change on the correlation coefficient, especially a reversal in the sign of the coefficient.

For a given small climate change, we conclude that the shape of the annual-yield response surface is the primary determinant of expected yield; none of the three BND parameters seems to play a major role. The NRCV, on the other hand, appears to be determined by an interplay of three factors: the shape of the yield surface, the correlation coefficient and the climate-change vector.

RELAXING THE ASSUMPTION ABOUT FUTURE PATTERNS OF ANNUAL CROP WEATHER

Early on, we decided to use essentially the same BND parameters in the five climate scenarios as in the Base Period, despite the fact that Test I had provided projections of changes in s_p for the latitude zones of agricultural interest.[2] The decision stemmed from (1) an asymmetry between s_T and s_p (we had some basis for varying the latter but none for varying the former), (2) a feeling that use of the same BND parameters in all the scenarios was reasonable in view of the modest climate changes delineated in Task I, and (3) a desire to keep the model simple.

After making the sensitivity analysis described in Section 5-10, we became more comfortable with the decision to use a single set of BNDs for all the scenarios. Even if projected changes in s_T had been available, they could not have affected the CVs appreciably, much less the NRCVs or expected yields. Also, in retrospect, it appears that altering s_p according to the Task I projections would have had little effect on the absolute variability of yields. These projections, like the projections of changes in precipitation itself, reflected a lack of consensus on the part of the Climate Panel. The mean values of the distributions of changes in s_p were small because of the uncertainty about just the direction of the changes. In the three most probable climate scenarios, all but one of the expected changes of s_p were zero. In the Large Cooling Scenario, the expected change of s_p was only +5% in the middle latitudes and +12.5% in the subtropics. And, in the Large Warming Scenario, the expected change of s_p was only −5% for all the key crops. We judge that ±5% changes in s_p would not change the CVs or NRCVs by more than 5%.

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[2] See the tables in Chapter II, *Climate Change to the Year 2000.*

The fact remains, however, that in our model the variability of relative yields is sensitive to the values of s_T and s_p. Therefore, if one could elicit from climatologists a clearer consensus about appreciable shifts in s_T and s_p with climate change, one would be obliged to tailor the BNDs to the individual climate scenarios.

APPENDIX D–5

VALIDATION OF THE CLIMATE-RESPONSE MODEL IN THE BASE PERIOD

INTRODUCTION

In Section 5–11 and Appendix D–4 we surmised that modest changes in the BND parameters s_T and s_p should not make much difference for questions of the *relative* variability of projected annual yields. However, it was shown in Section 5–10 that these parameters, especially s_p, can have a strong effect on ***absolute*** variability, i.e., on the standard deviation of calculated yields. Absolute variability—hence s_T and s_p and a host of other factors—becomes a concern when one considers the validity of the climate-response model in a rather narrow, literal context, namely, the degree of congruence between the statistics of recent historical yields and the statistics of yields calculated for the Base Period. In this appendix we describe an attempt to assess the "literal" validity of the Base-Period yield distributions, recognizing that s_T and s_p might be "wrong" enough to frustrate literal validation, but not "wrong" enough to affect the overall relativistic outlines of the climate-crop scenarios.

A PERSPECTIVE ON LITERAL VALIDATION

The goal of validation is to build confidence in a model. Model validation is a tradition of the physical sciences, where one can run a model and check the results against reality. Our simplified, policy-oriented, predictive model does not lend itself to this kind of demonstration. It was designed to project the effects of future climate, but we can check only the yields calculated for the Base Period (the recent past). Moreover, the climate-response model deals with two determinants of annual yields, the highly aggregated annual crop-weather variables. Real crops are affected by many other factors, including the day-to-day and week-to-week weather changes that are subsumed in our two variables. Hence, a literal demonstration of the model requires that one somehow isolate the effects of averaged weather on recorded yields. Finally, unlike the physical scientists, we use a mixture of "hard" data based on observations (the BND parameters) and "soft" data based on expert judgment (the annual-yield functions and the climate scenarios). Given the model's focus on averaged weather and future climate, as well as the uncertainties in the soft data, we think that literal validation is not a definitive test, but it does check the model for bias.

The decisionmaker must weigh the validation results and the uncertainties in the inputs against other considerations—the expertise of those who contributed the soft data, the logic of the model, the internal consistency of the results, and the insensitivities discussed in Appendix D-4.

FACTORING OUT THE EFFECTS OF TECHNOLOGY

There is a statistical disparity between a small, unique sample of historical yields and the calculated distribution of Base-Period yields, which is continuous in principle. But the main obstacle to literal validation is the removal of technology effects from a time series of actual yields, leaving only the effects of crop weather.[1] There is no generally accepted method for separating weather effects from other factors, and the results are in many cases quite sensitive to the procedures used. Weather effects are commonly separated by removal of a linear time trend. We applied this method to the yield series in Appendix B-1, primarily because of its simplicity and the realization that no "best" procedure has been identified.

Our treatment of the historical yields involves the following assumptions:

- *Weather effects have no real trend over the period measured.* Thus, it is assumed not only that climate is constant, but that year-to-year fluctuations of crop weather do not accidentally cause a time trend. The latter may be a weak assumption if, for example, a 27-year period begins with a few years of drought and ends with a few wet years, in which case a time trend will be introduced into the yield series. This accidental effect would be lost with the removal of the time trend, thereby causing the presumably weather-induced residual variance to be too low.
- *Technology increases yields at a linear rate.* This assumption probably is more realistic for developing countries than for developed countries, but it may have two flaws. First, yield increases due to technology may not be linear or even smooth,

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[1] As used here, "technology" means everything, except weather, that affects yields; it includes policy and economic variables and such inputs as fertilizer, pesticides, improved crop varieties, and better farming methods.

in which cases the measured residual variance is too high. Secondly, technology causes *potential* yield to increase each year, not necessarily *actual* yield. Especially in developed countries, economic considerations probably can induce about as much variance in the yield series as does weather. This added variance is not independent of weather and may act to reduce or increase total measured variance.

THE RESULTS OF THE VALIDATION TEST

We chose the standard deviations of the yield distributions to test the performance of the model. The mean could not be used because the model produces estimates normalized to the mean, and skewness could not be used because the standard error of skewness of a 27-year sample is prohibitively high. The detrended normalized series of historical yields[2] was considered to be the universe with a standard deviation represented by σ, while the Base-Period yield distribution was considered to be the sample with a standard deviation represented by s. The ratio of s/σ is unity if the model precisely estimates the real world.

As shown in Table D-5.1, the model produced frequency distributions with apparently high standard deviations (vis-a-vis those of the detrended series) for U.S. soybeans, Australian wheat and Indian rice (s/σ ratios of 1.79, 1.72 and 1.48 respectively). On the low side were U.S. winter wheat, Brazilian soybeans and Canadian wheat (s/σ ratios of 0.49, 0.61 and 0.64). The geometric mean of the s/σ ratios is 1.019, which indicates that the model is not biased.

EVALUATING THE VALIDATION RESULTS

At first we were disappointed with the validation results. On reflection, we are inclined to view the validation exercise mostly as an object lesson on the difficulty of disentangling the many factors which affect yields. The climate-response model is based on measured climate statistics and judgments of how these statistics affect yields. Errors are possible in both data sets.[3] In addition, two crop-weather variables may be insufficient to replicate the behavior of real crops (but still sufficient for long-range yield projections).

We know from Section 5-10 that one could adjust the BND parameters to produce results much closer to the detrended time series.

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[2] The linear-trend value of yield was calculated by $\hat{Y} = a + bt$, where a and b are regression coefficients and t is crop year. The detrended normalized yield Y_d corresponding to a reported yield Y is given by $Y_d = (Y - \hat{Y})/\hat{Y}$.

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[3] We have not attempted to sort out the relative influences of the BND and the annual-yield matrix on a Base-Period yield distribution.

Table D-5.1

COMPARISONS OF THE STANDARD DEVIATIONS: The detrended series of historical yields versus the base-period yield distributions calculated by the climate response model

COUNTRY	CROP	STANDARD DEVIATION		s / σ
		DETRENDED SERIES (σ)	MODEL (s)	
ARGENTINA	*Corn*	0.14	0.17	1.20
	Wheat	0.15	0.15	1.01
AUSTRALIA	*Wheat*	0.15	0.26	1.72
BRAZIL	*Soybeans*	0.18	0.11	0.61
CANADA	*Wheat*	0.19	0.12	0.64
INDIA	*Rice*	0.07	0.11	1.48
	Wheat	0.12	0.13	1.01
U.S.	*Corn*	0.09	0.10	1.18
	Soybeans	0.06	0.11	1.79
	Spring Wheat	0.15	0.11	0.78
	Winter Wheat	0.21	0.10	0.49
USSR	*Spring Wheat*	0.21	0.15	0.74
	Winter wheat	0.12	0.13	1.08

Note: The PRC statistics were not compared because no weather data were available for the PRC.

However, one would compromise the objectivity of the model by tuning it to a predetermined answer that may itself be somewhat questionable. Practically, there are no solid grounds for declaring a fit to be "bad." If there were, there is no easy way to judge the cause or causes of a bad fit. Low expertise or small participation might make one suspect an annual-yield function, but high expertise and large participation do not guarantee a valid yield function. Undoubtedly, some of the BND parameters could be refined by searching out additional climate records, but in most cases this alone probably would not alter the projections of expected yields or the *relative* variability of yields, regardless of the outcome of a literal validation test. Yet it would be comforting to know—if very difficult to establish—that the calculated absolute measures of yield variability bear some resemblance to reality.

If the user finds the validation results unacceptable and can determine the cause of the disagreement, he may adjust the Base-Period inputs as he sees fit. Alternatively, he can undertake the development of a more sophisticated climate-response model to capture whatever it is that explains the 27-year series of yields.

CONCLUSIONS

The fact is that literal validation can be too rigorous a test for a highly aggregated model. The inputs, assumptions and basic logic of the climate-response model possess a certain cogency. We believe that the cogency and observed behavior of the model commend it for projecting the *differential* effects of an assumed climate change on the average values and variability of crop yields.

APPENDIX E–1

THE PROJECTED EFFECTS OF EXTREME CLIMATE CHANGES ON THE DISTRIBUTIONS OF ANNUAL YIELDS

This appendix contains the arrays of histograms referred to in Sections 1-11, 5-8, and 6-2. Each array depicts the distributions of normalized relative annual yields calculated for eight climate changes and the Base Period, our representation of "present" climate.

All the distributions are based on the indigenous agricultural technology of 1976. The climate changes are specified by (1) a change in the long-term average of annual mean heading-period temperature ($\Delta\overline{T}$), and (2) a change in the long-term average of mean crop-year precipitation ($\Delta\overline{P}$). For all the climate changes it is assumed that the pattern of year-to-year fluctuations in temperature and precipitation is similar to that of the Base Period. The climate-response methodology is outlined in Sections 1-9 through 1-11.

The central histogram in each array corresponds to the Base Period (no climate change); the other distributions are climate-induced perturbations thereof. The top row of histograms pertains to a three-degree warming of the crop region, the bottom row to a three-degree cooling. The left-hand column pertains to a climate 30% drier than present, and the right-hand column to one that is 30% wetter. The yields on the horizontal scales are expressed as percentages of the expected (or average) yield in the Base Period.

Selected statistics from each yield distribution are presented in Appendix E-2. Also, in the introduction to Appendix E-2 we consider whether the arrays include the distributions with the minimum and maximum expected yields that are possible for temperature changes up to 3°C and precipitation changes up to 30%.

Figure E-1.1

CORN: *Argentina*

Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$=Expected Yield)

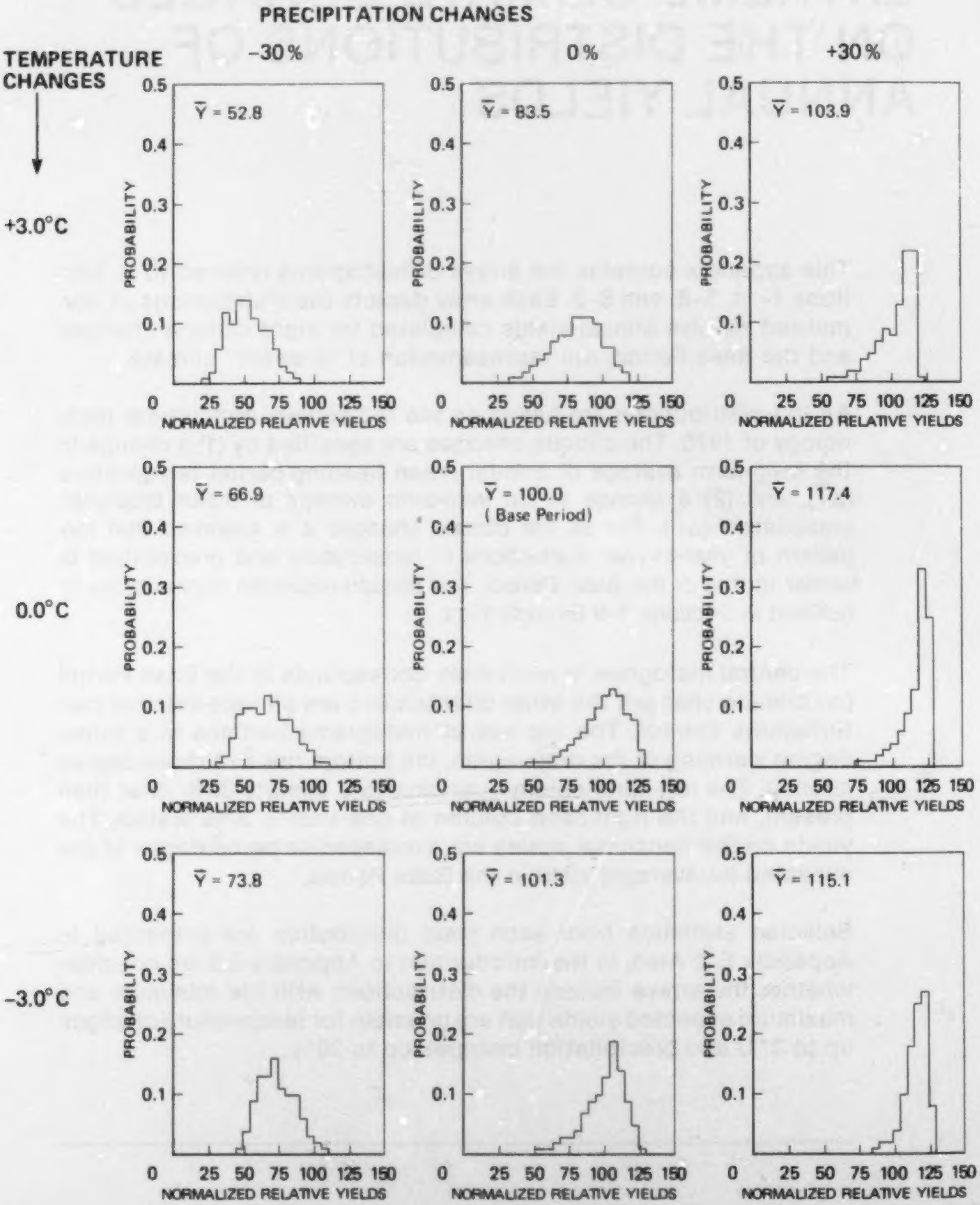


Figure E-1.2

CORN: *U.S.*
Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$ = Expected Yield)

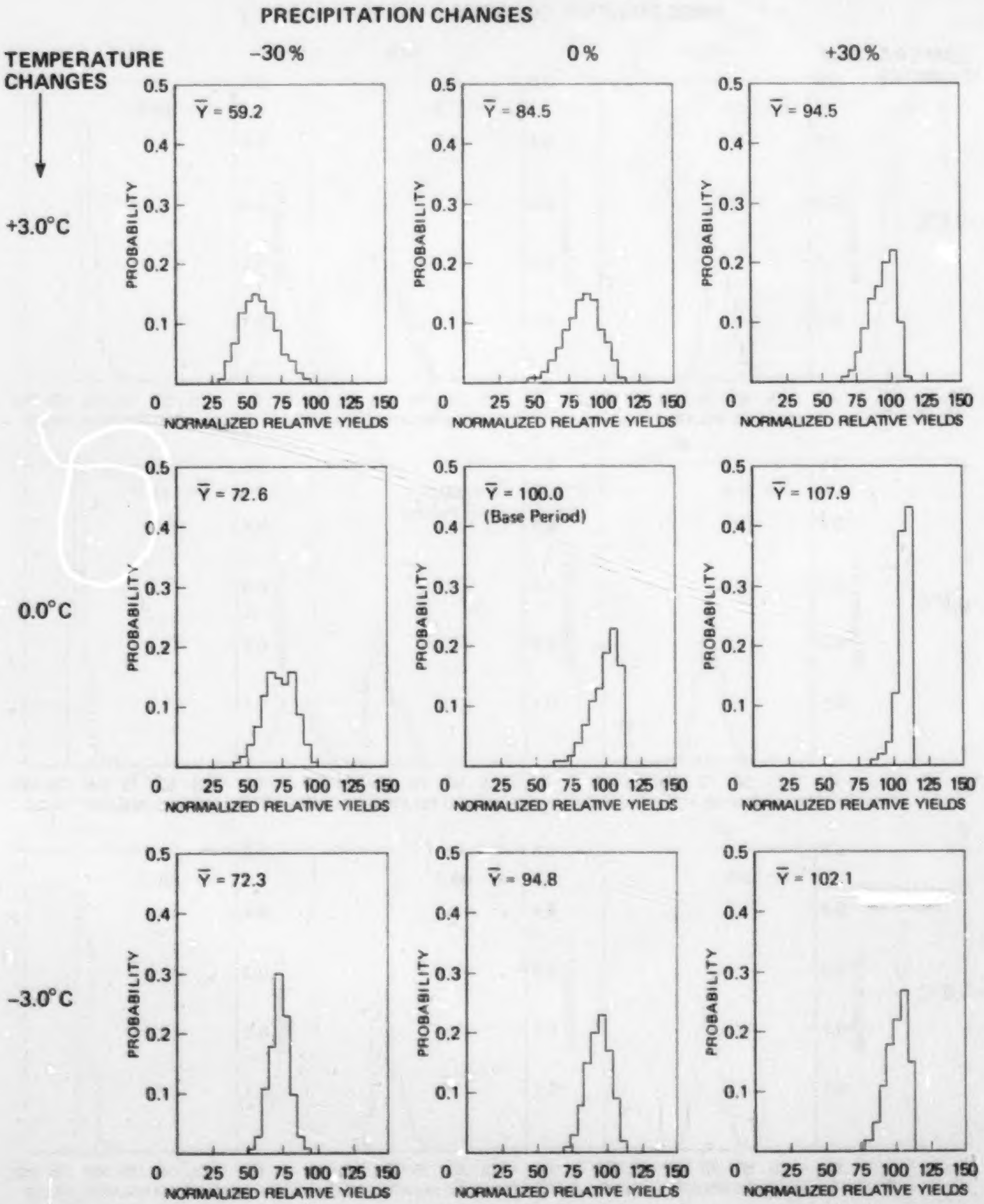


Figure E-1.3

RICE: *India*

Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$=Expected Yield)

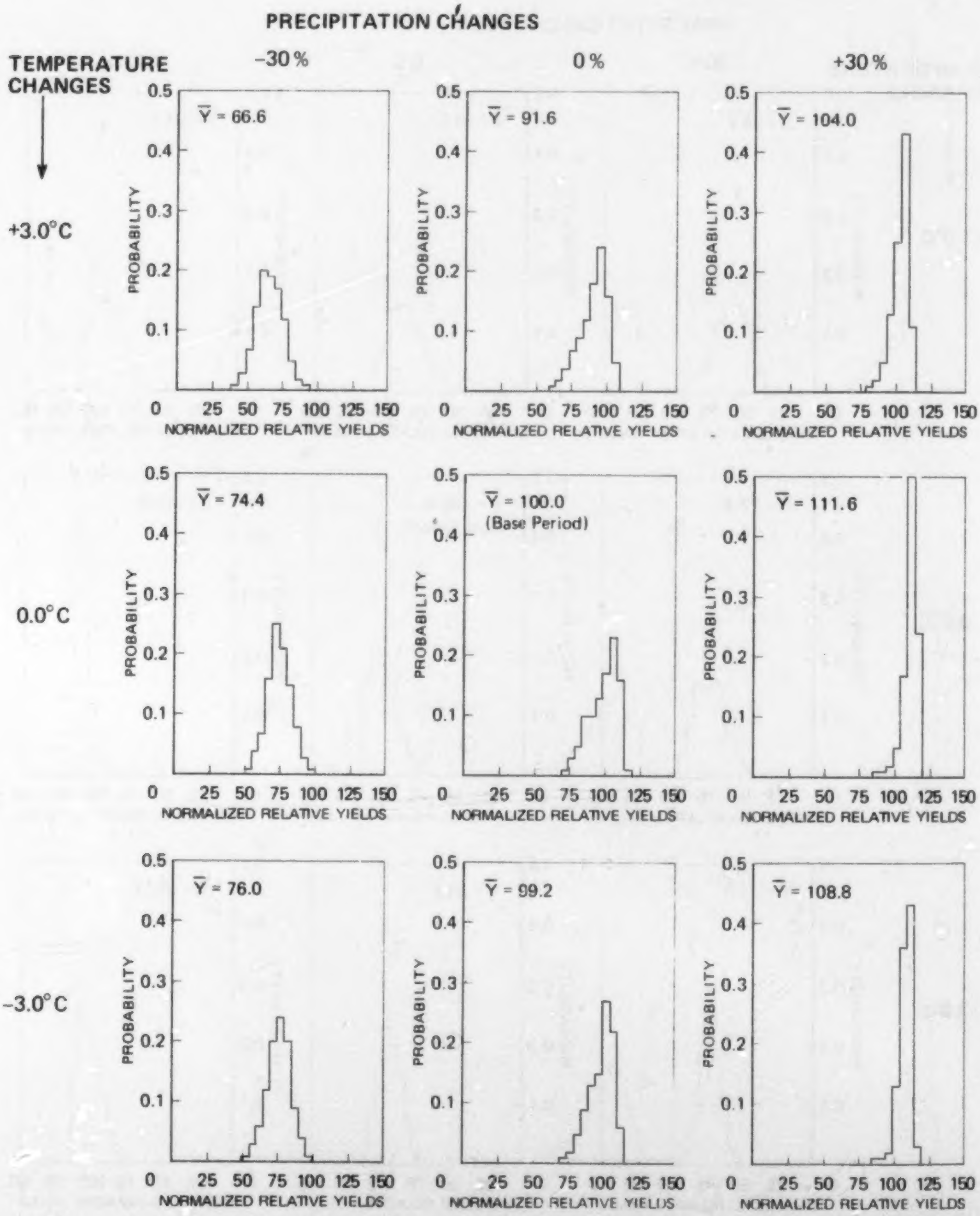


Figure E-1.4

RICE: *PRC*

Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$ = Expected Yield)

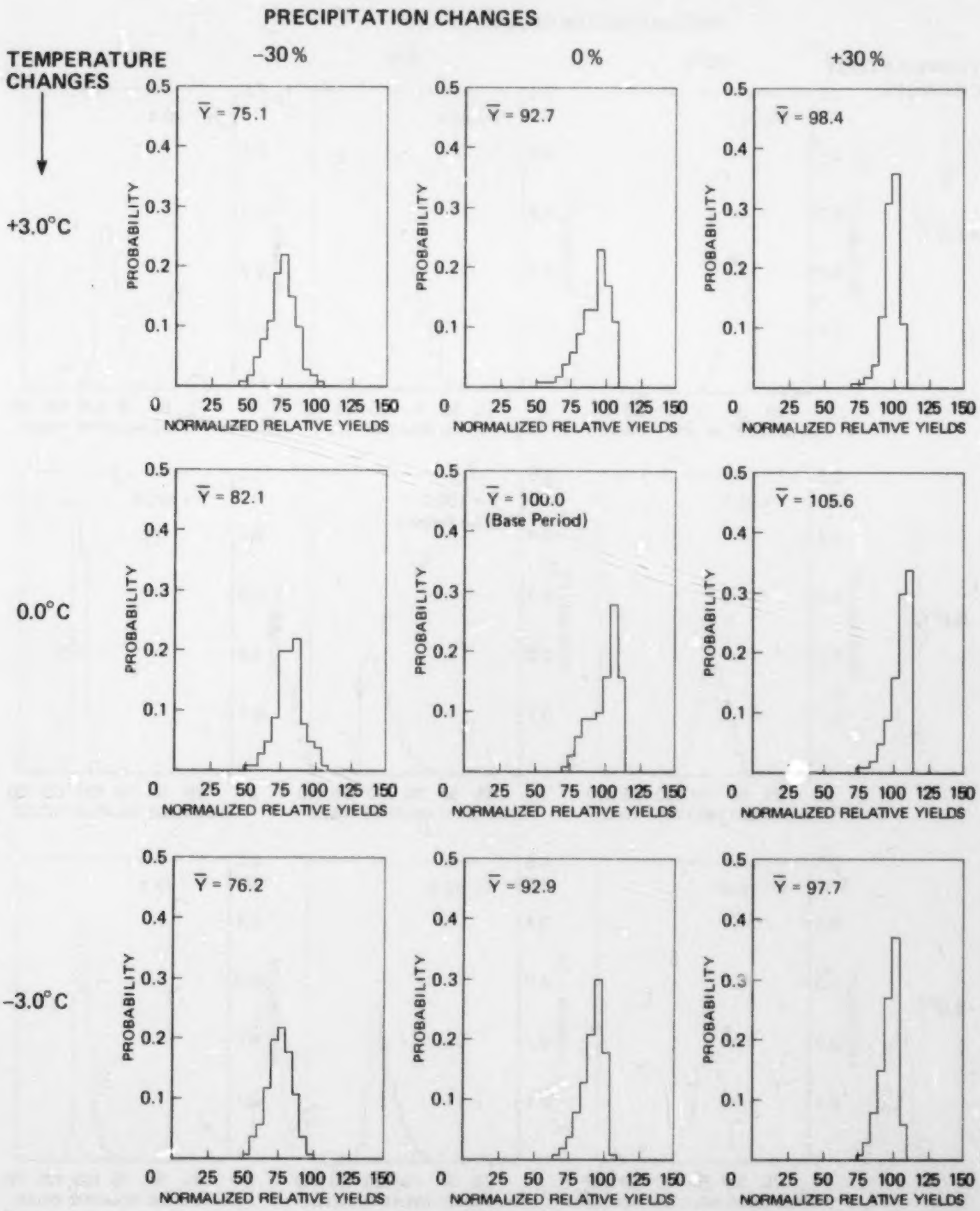


Figure E-1.5

SOYBEANS: *Brazil*
Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$=Expected Yield)

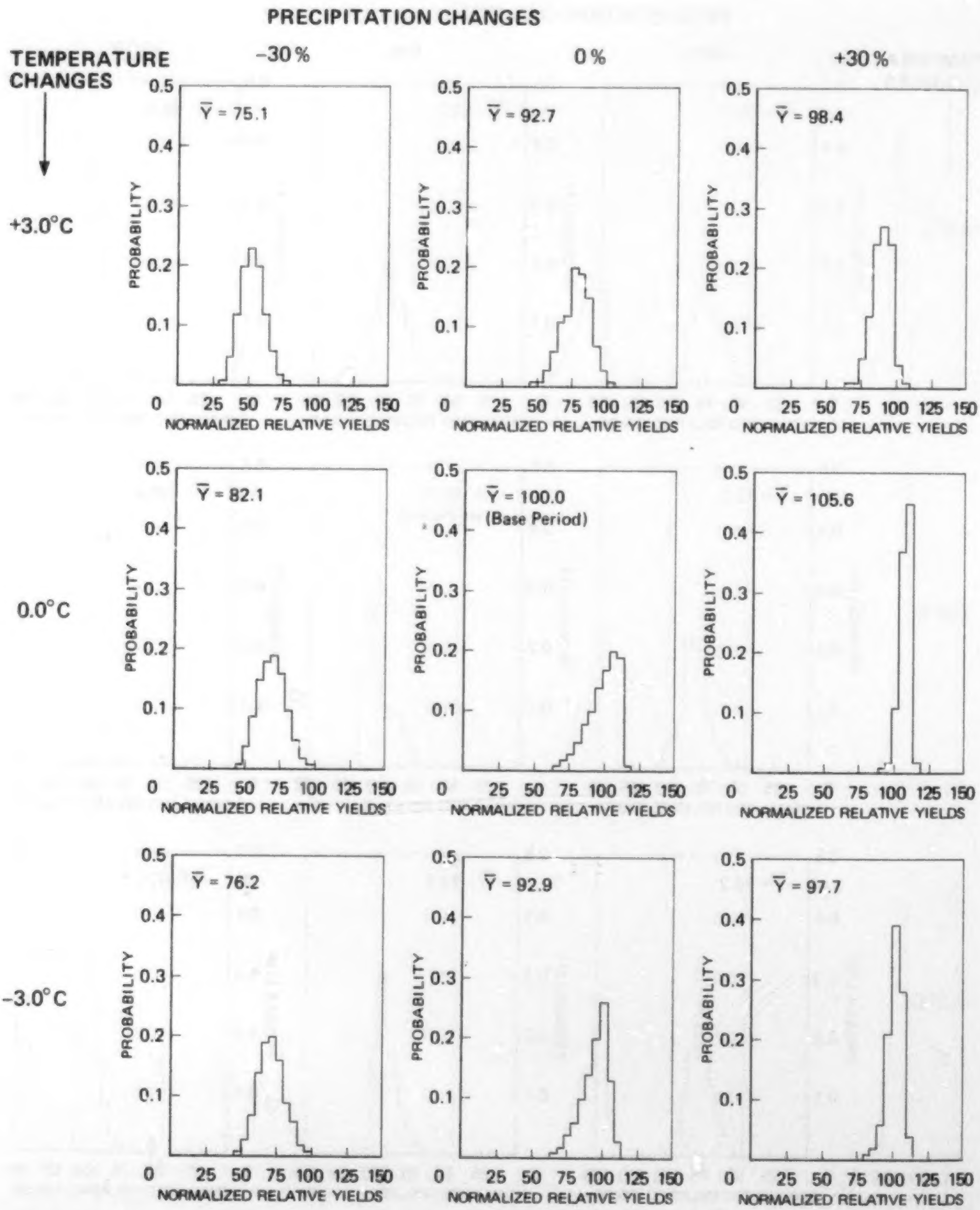


Figure E-1.6

SOYBEANS: *U.S.*
Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$ = Expected Yield)

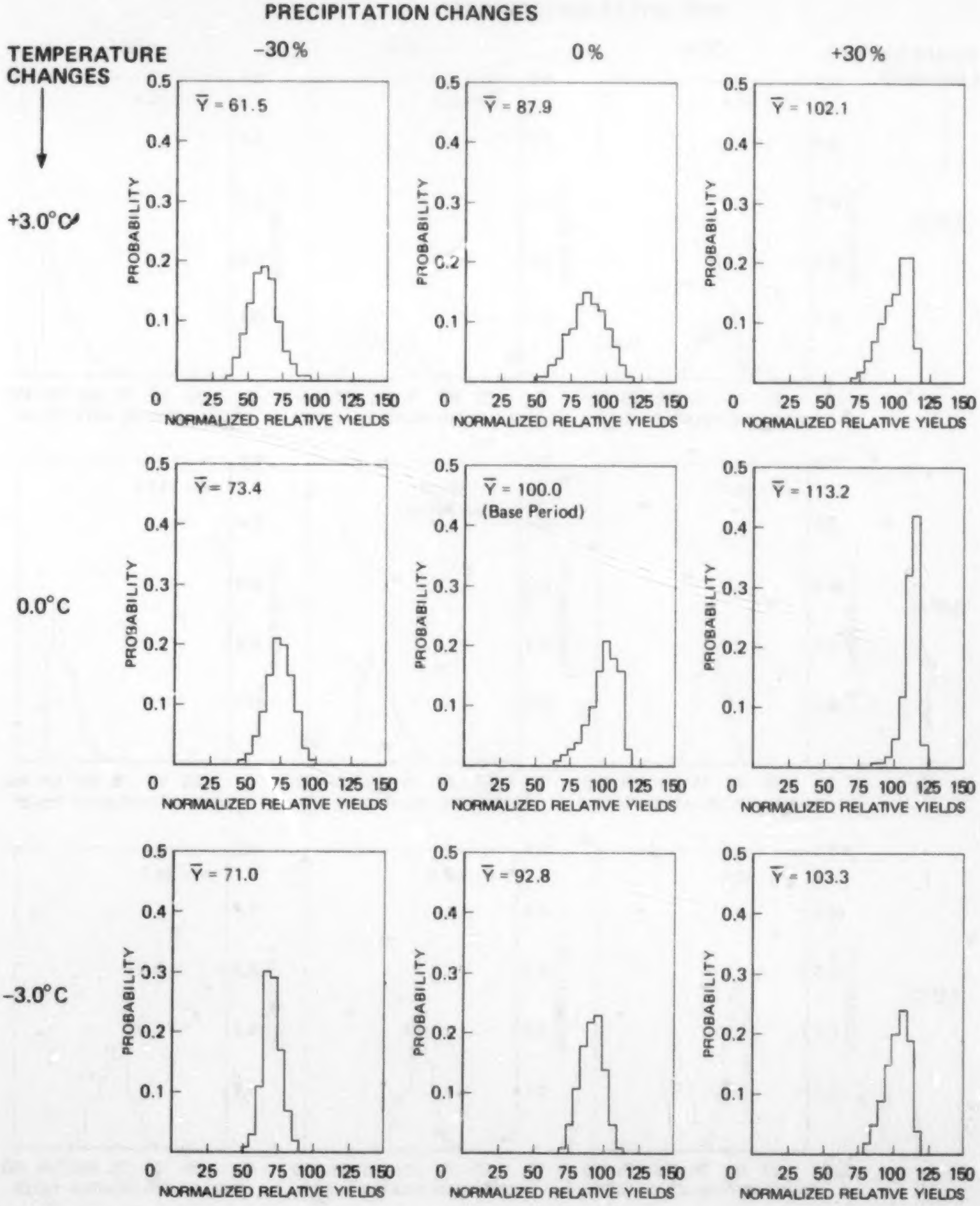


Figure E-1.7

SPRING WHEAT: *Canada*

Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$=Expected Yield)

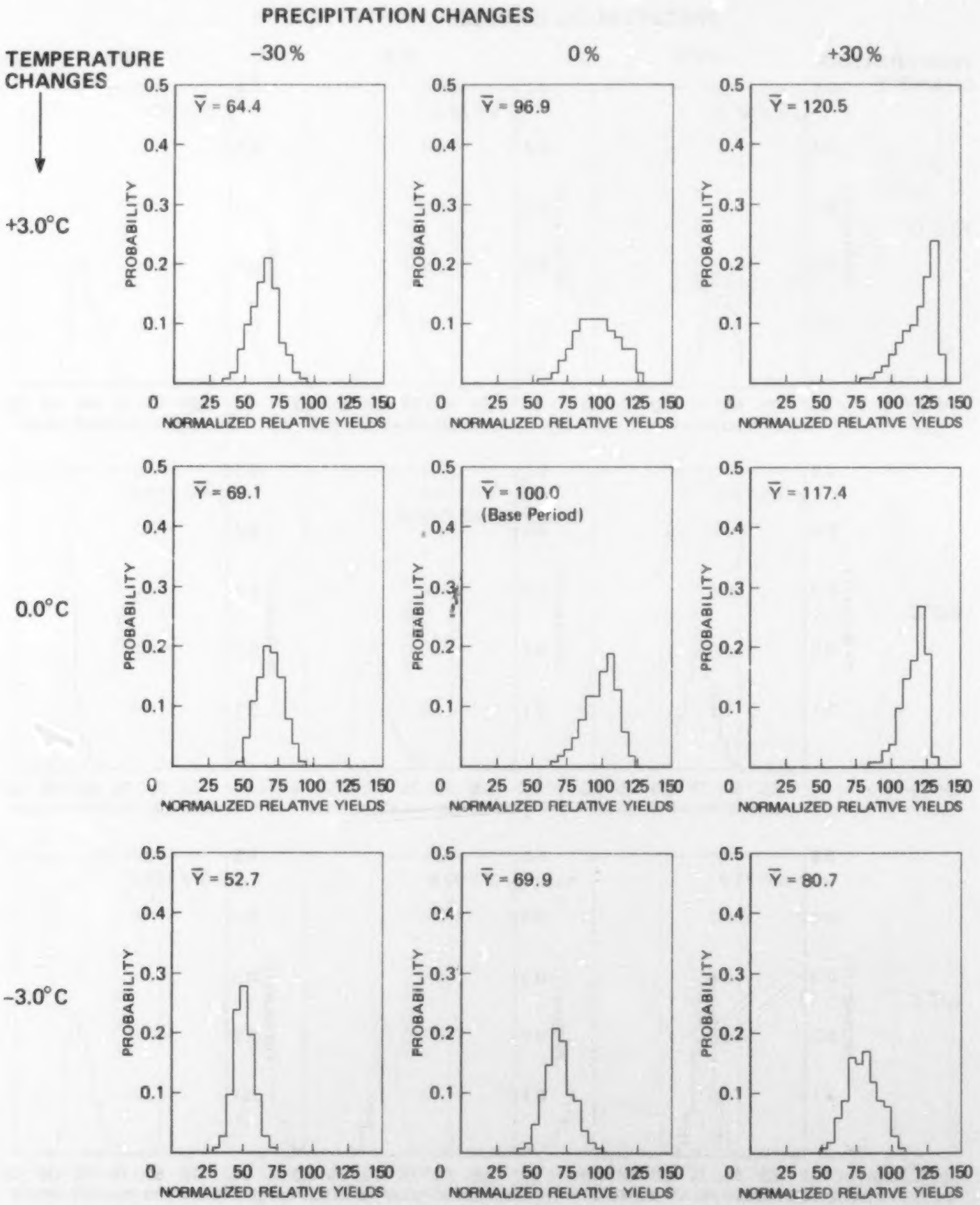


Figure E-1.8

SPRING WHEAT: *U.S.*

Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$=Expected Yield)

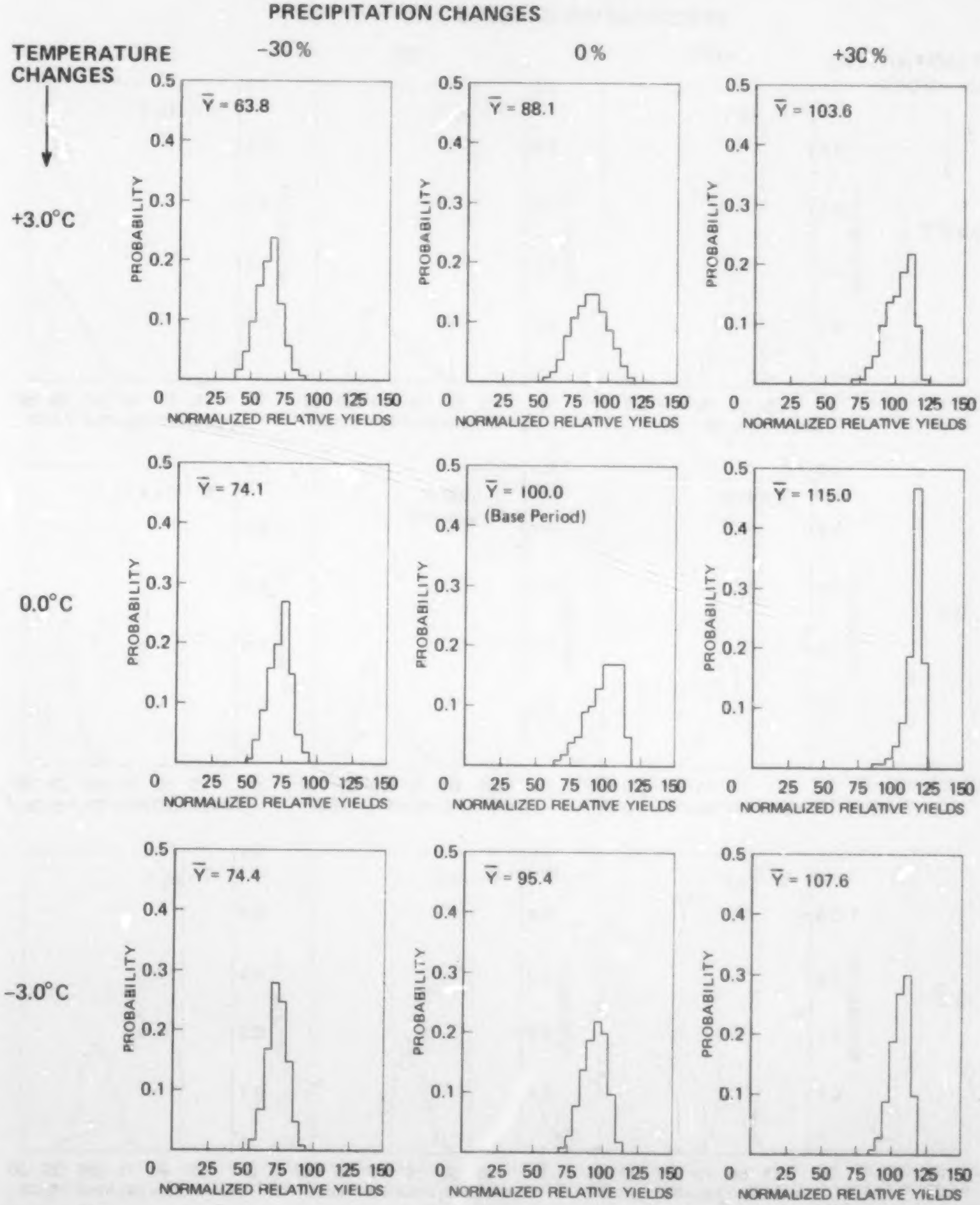


Figure E-1.9

SPRING WHEAT: *USSR*
Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$=Expected Yield)

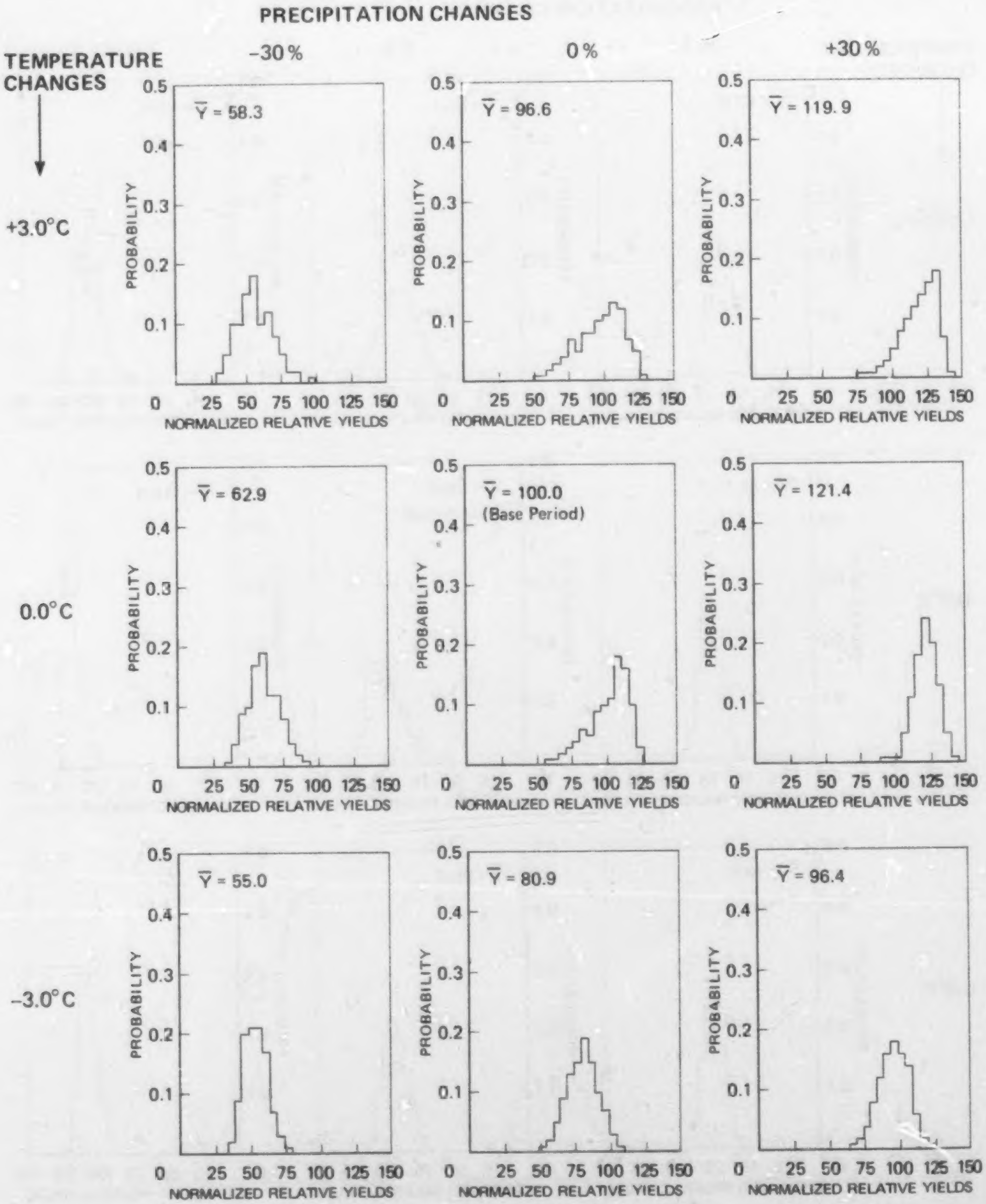


Figure E-1.10

WINTER WHEAT. *Argentina*
Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$ = Expected Yield)

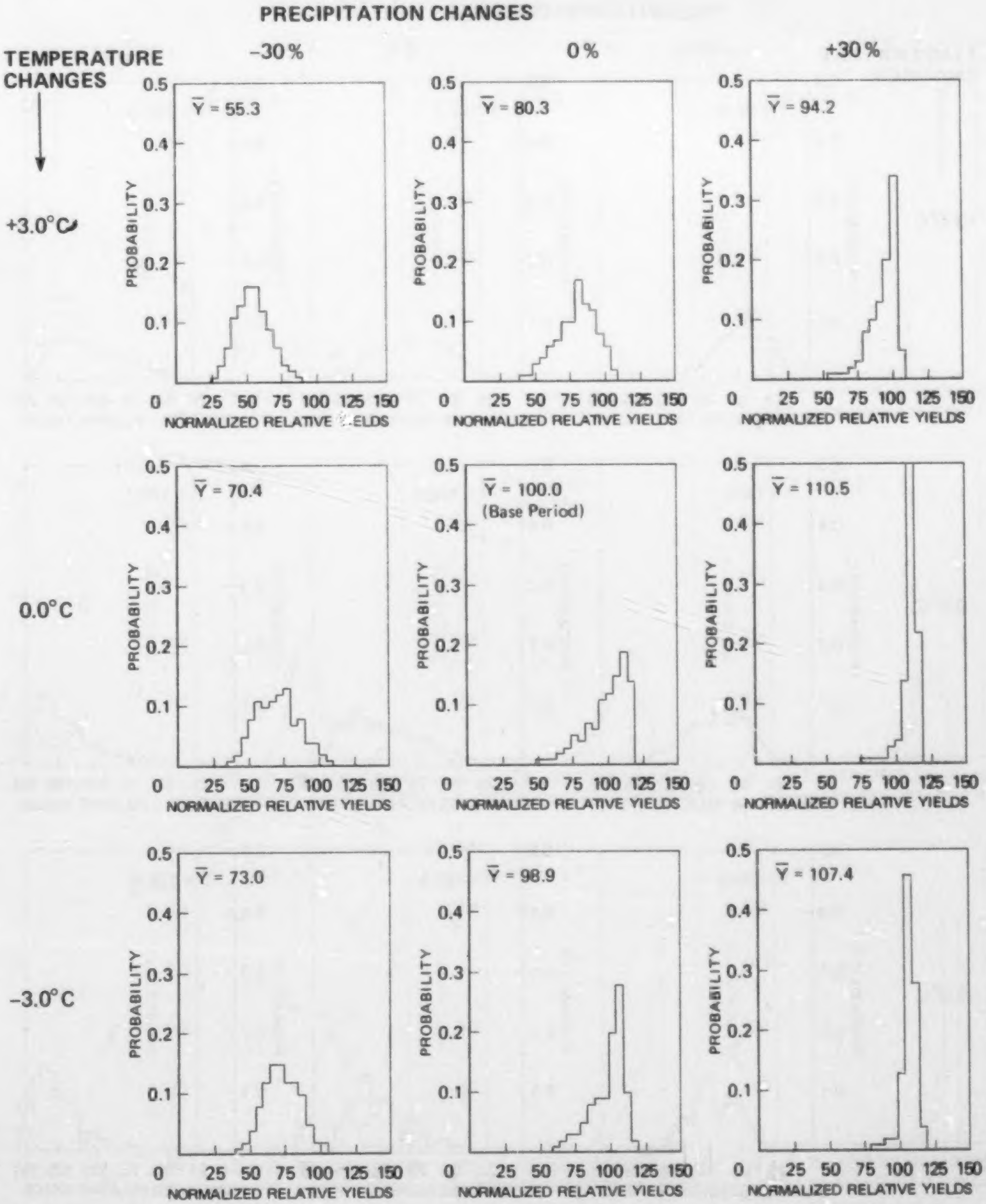


Figure E-1.11

WINTER WHEAT: *Australia*

Effect of Climate Changes on the Frequency Distribution of Annual Yields

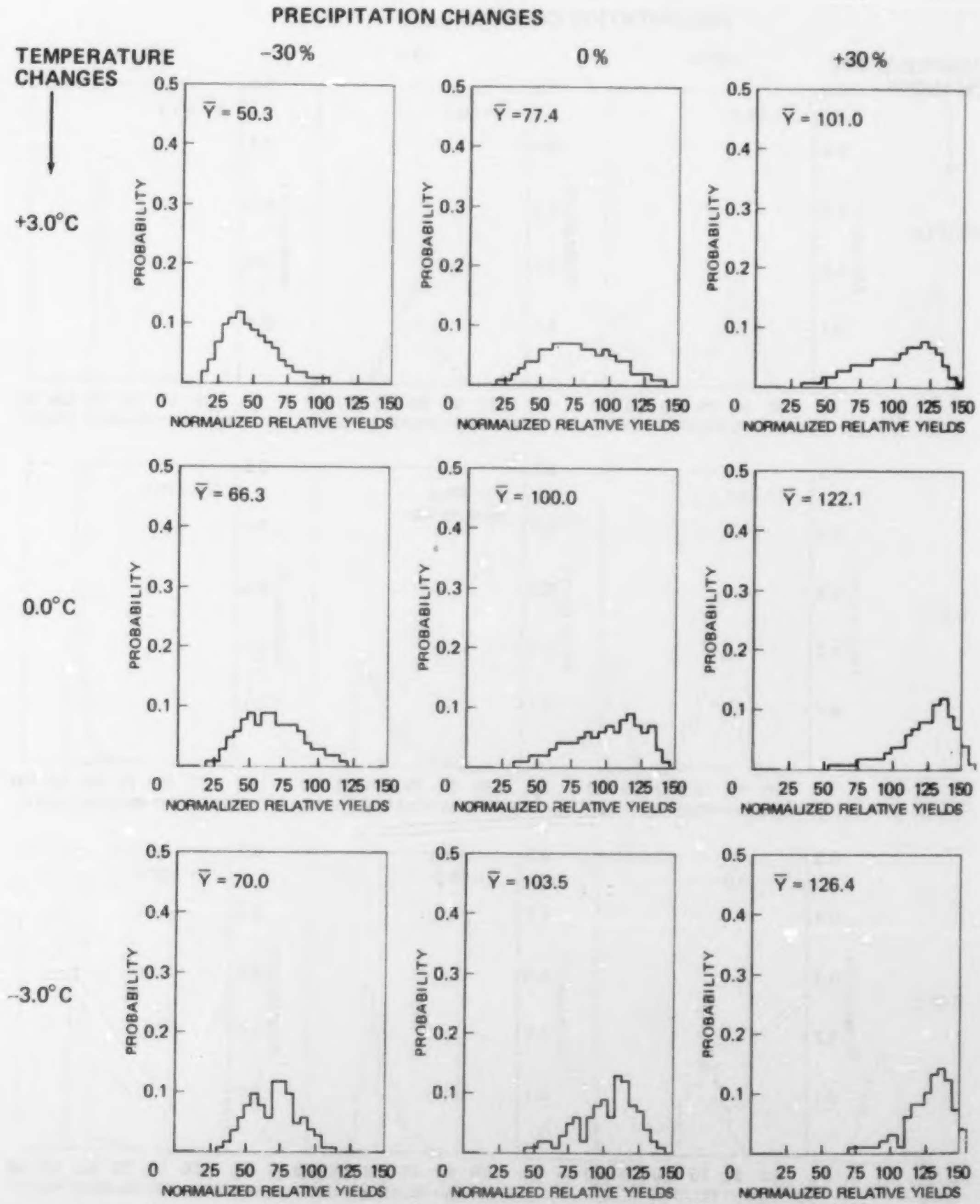


Figure E-1.12

WINTER WHEAT: *India*

Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$=Expected Yield)

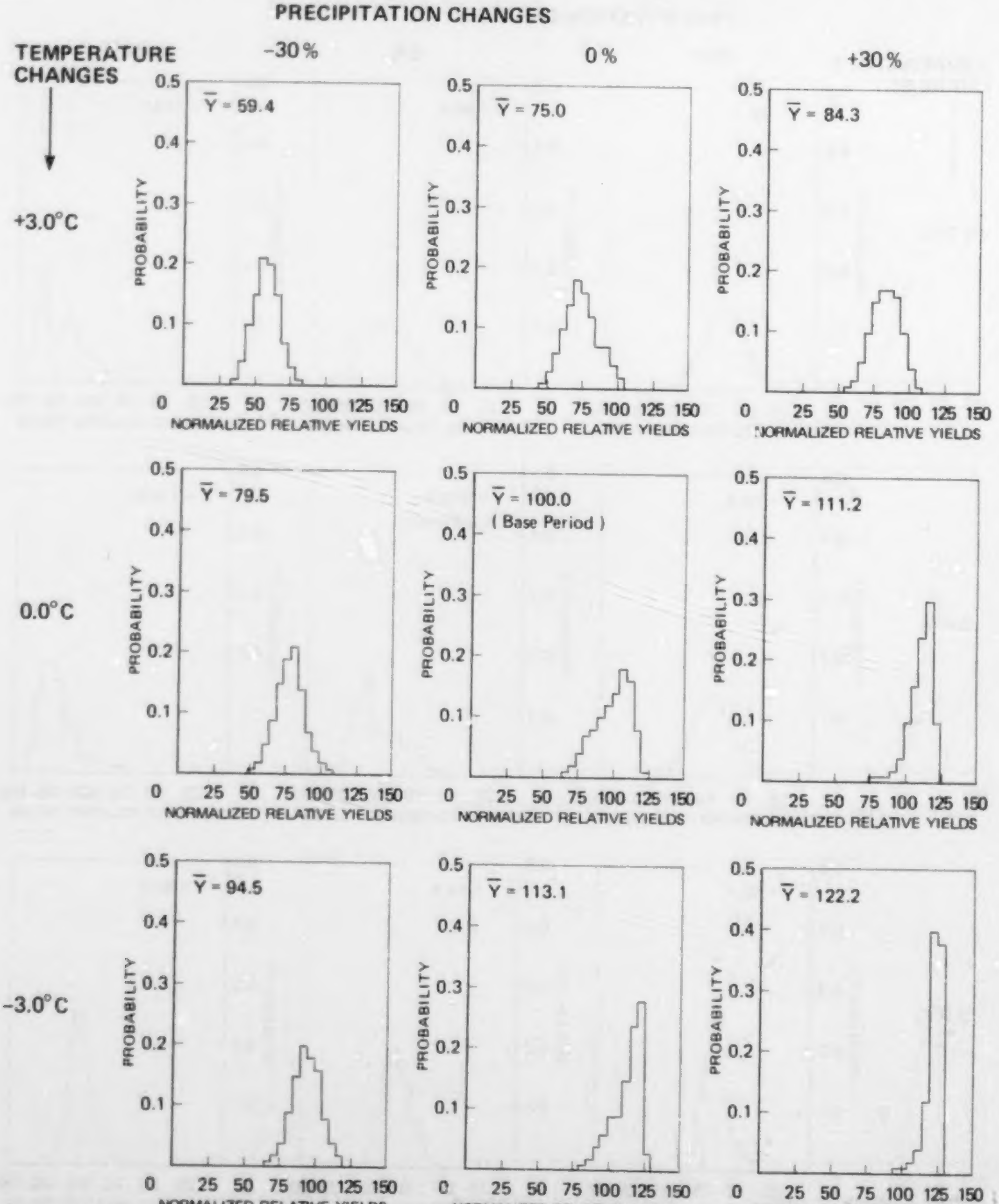


Figure E-1.13

WINTER WHEAT: ***PRC***

Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$ = Expected Yield)

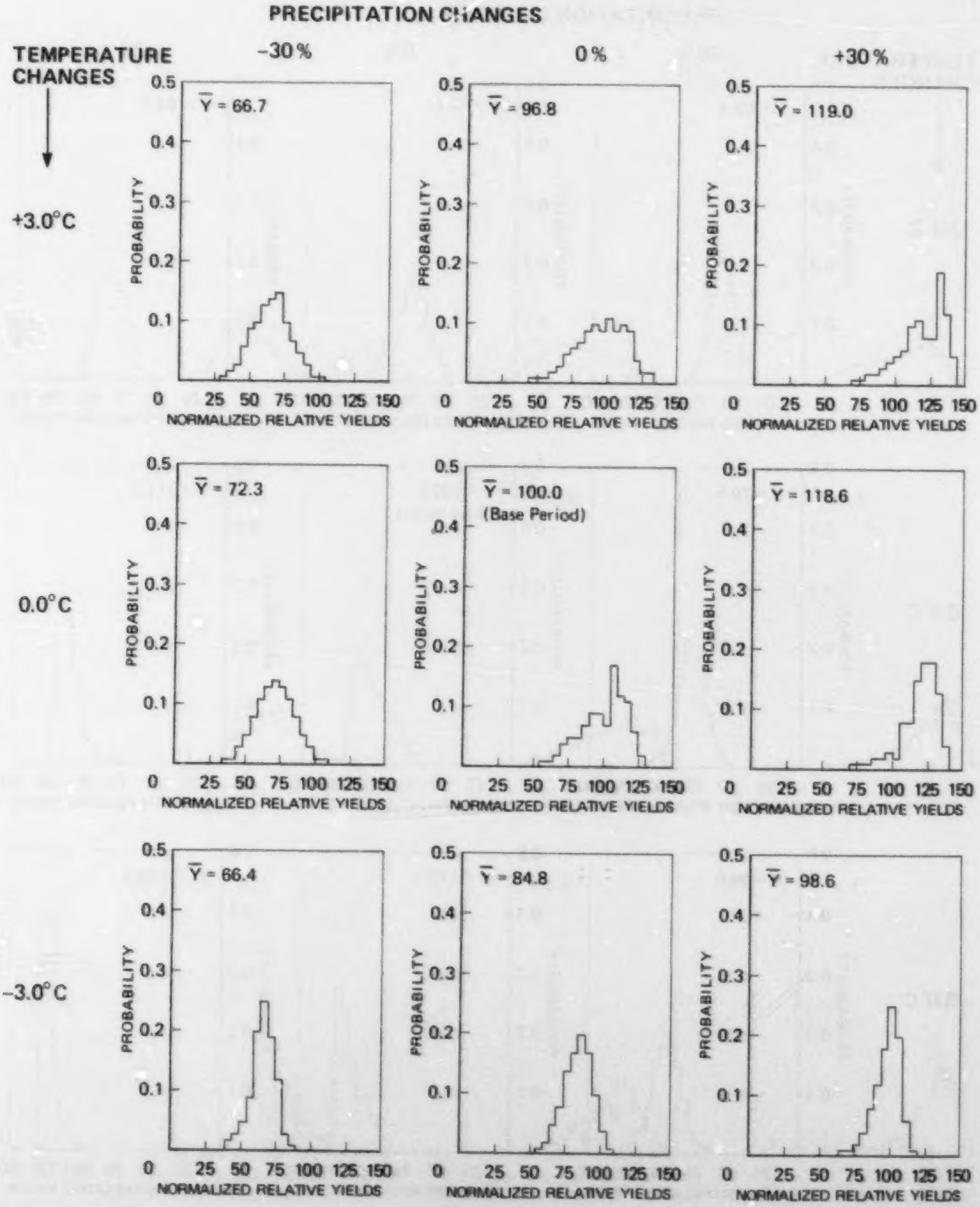


Figure E-1.14

WINTER WHEAT: ***U.S.***

Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$ = Expected Yield)

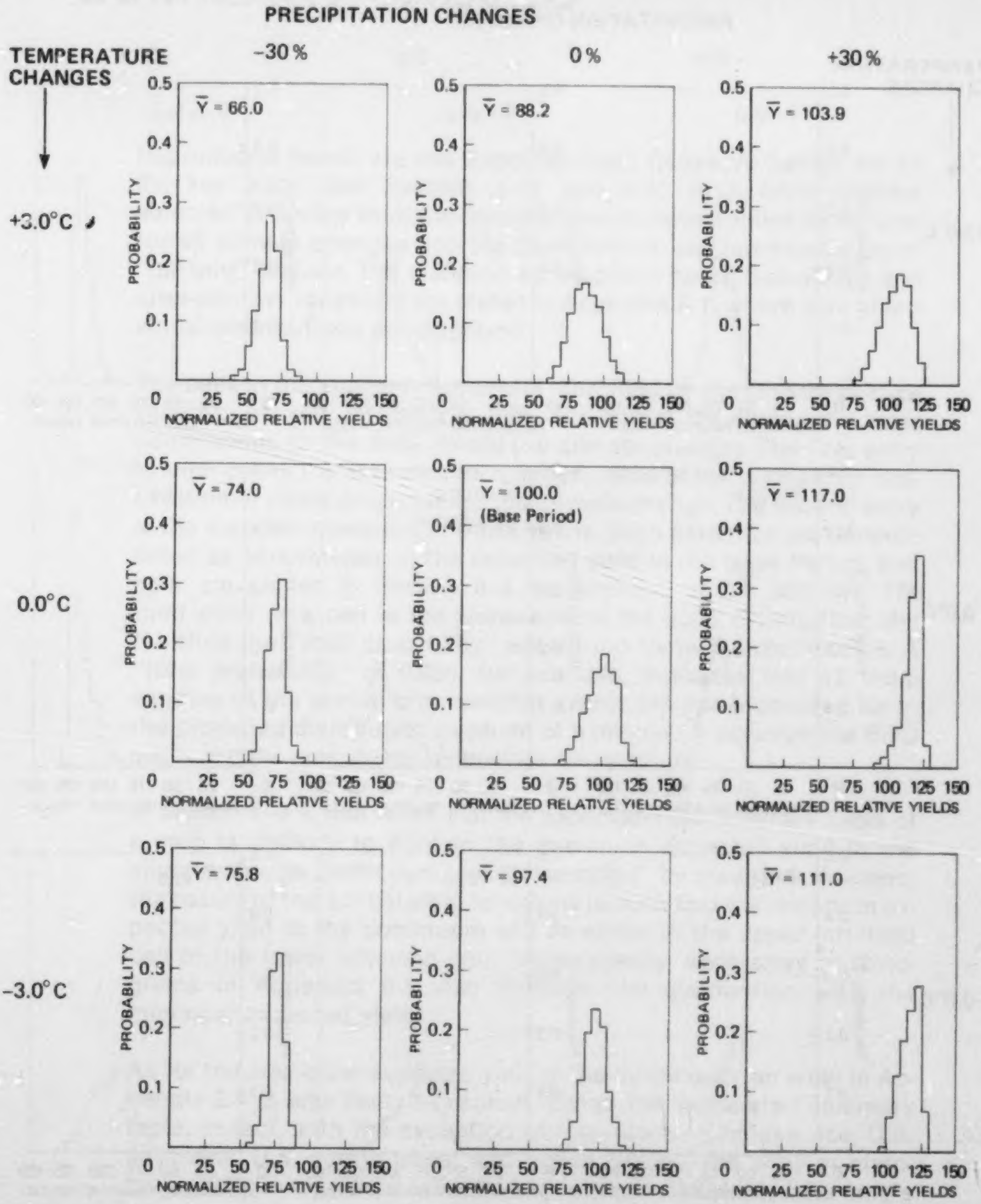
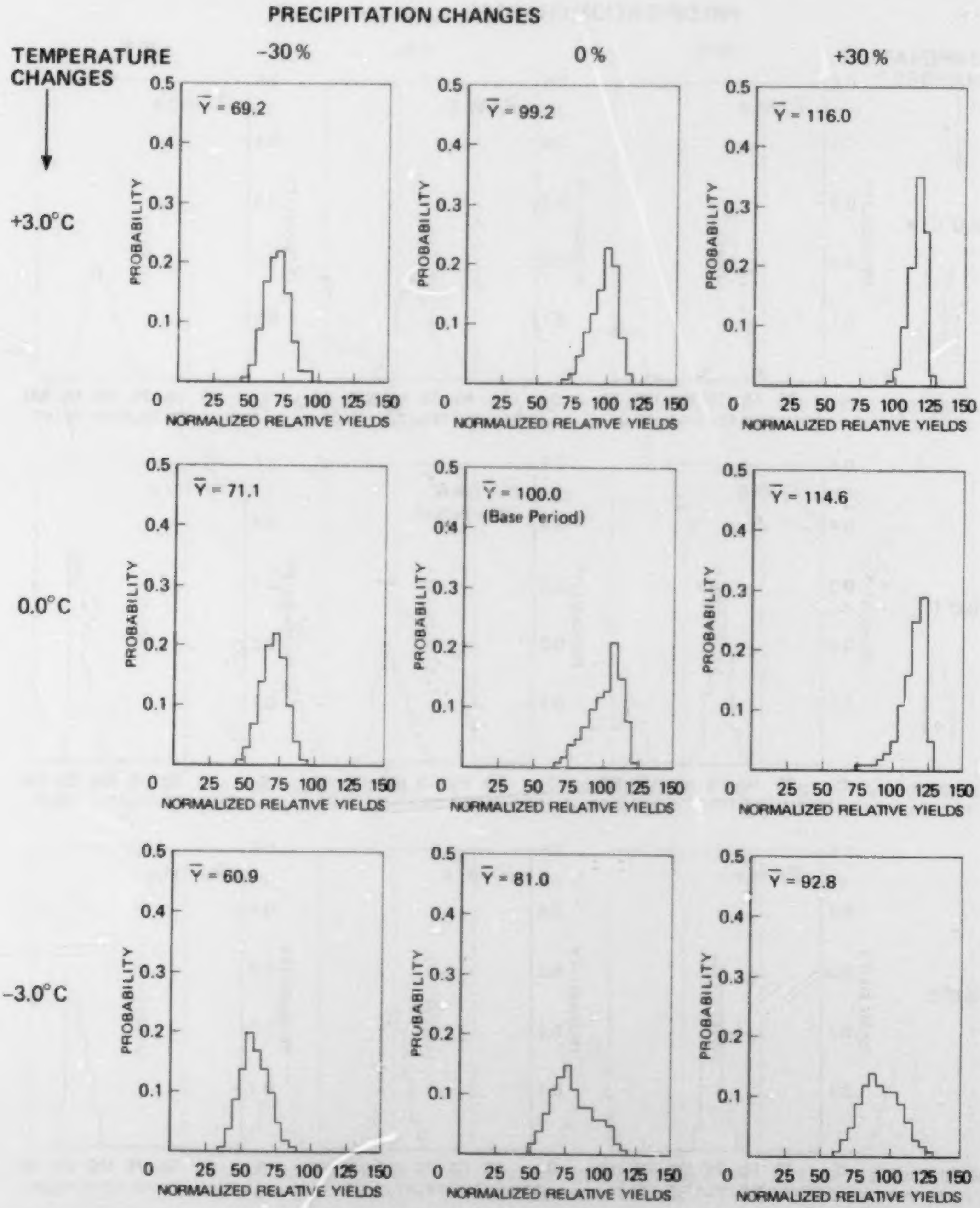


Figure E-1.15

WINTER WHEAT: *USSR*

Effect of Climate Changes on the Frequency Distribution of Annual Yields ($\overline{Y}$=Expected Yield)



APPENDIX E–2

THE EXPECTED-YIELD SUMMARY TABLES

Reproduced herein are the Expected-Yield Summary Tables for all the key crops (see Sections 1–11 and 6–3). Each table contains selected statistics from the distributions of annual yields calculated for 48 climate changes and the Base Period, our representation of "present" climate. The common assumptions about technology and crop-weather variability are stated in Appendix E-1, where nine of the actual distributions are displayed.

The cells in the summary tables are identified by the climate-change variables $\Delta\overline{T}$ and $\Delta\overline{P}$ (Section 1–9). The cell at the center of a table corresponds to the Base Period (no climate change). The first entry in each cell is the expected (or average) value of the normalized relative annual yields projected for the climate change. The second entry is the standard deviation of these yields. Both statistics are denominated as percentages of the expected yield in the Base Period, and both are plotted in Section 6–4 as functions of $\Delta\overline{T}$ and $\Delta\overline{P}$. The third entry in a cell is the skewness of the yield distribution; the fourth is the "total probability" accounted for in the distribution. A "total probability" of 0.988, for example, indicates that 12 thousandths of the annual crop-weather events are *not* accounted for in the projected distribution because of a mismatch between the BND matrix and the annual-yield matrix (see Section 6-2).

In Section 6–3 it was noted that the Expected-Yield Summary Table of a crop is unlikely to contain the maximum expected yield in the climate-change continuum that is "sampled" by the table. However, the nature of the annual-yield functions is such that the minimum expected yield in the continuum will lie either in the upper left-hand cell or the lower left-hand cell. Consequently, each array of histograms in Appendix E-1 also includes the distribution with the *minimum* expected yield.

As for the *maximum* expected yield in the continuum, an array in Appendix E-1 is less likely to capture it than the associated summary table. In fact, with the exception of four crops—Chinese rice, U.S. soybeans, U.S. spring wheat and Indian wheat—the array of histograms fails to represent even the largest expected yield in the crop's summary table. The arrays for Indian rice, Brazilian soybeans, Australian wheat and U.S. winter wheat comprehend only the second largest of the expected yields in their respective summary tables. The array for Argentine wheat incorporates only the fourth largest tabulated expected yield, while the remaining arrays incorporate the third largest.

Table E-2.1

CORN: *Expected-Yield Summary Tables*

ARGENTINA

ΔT̄ (°C)	ΔP̄(%) -30	-20	-10	0	10	20	30
3	52.8 14.0 0.34 1.000	63.6 16.3 0.06 1.000	73.9 17.5 -0.19 1.000	83.5 17.9 -0.40 1.000	91.9 17.5 -0.65 1.000	98.8 16.3 -0.98 0.998	103.9 14.4 -1.40 0.988
2	58.0 15.0 0.29 1.000	69.4 17.0 -0.04 1.000	80.1 17.9 -0.30 1.000	89.8 18.0 -0.54 1.000	98.0 17.2 -0.82 1.000	104.6 15.6 -1.20 0.998	109.3 13.5 -1.68 0.988
1	62.8 15.9 0.22 1.000	74.8 17.7 -0.15 1.000	85.8 18.1 -0.44 1.000	95.4 17.7 -0.70 1.000	103.3 16.5 -0.99 1.000	109.5 14.8 -1.38 0.998	113.9 12.6 -1.88 0.988
0	66.9 16.3 0.19 1.000	79.3 18.0 -0.19 1.000	90.5 18.2 -0.52 1.000	100.0 17.5 -0.82 1.000	107.7 16.0 -1.17 1.000	113.5 13.9 -1.62 0.998	117.4 11.7 -2.17 0.988
-1	70.8 16.0 0.14 1.000	83.1 17.7 -0.22 1.000	94.2 18.0 -0.53 1.000	103.6 17.1 -0.87 1.000	110.9 15.3 -1.31 1.000	116.0 12.9 -1.87 0.998	119.2 10.5 -2.54 0.988
-2	73.4 14.7 0.12 1.000	84.9 16.5 -0.18 1.000	95.6 17.0 -0.49 1.000	104.7 16.3 -0.83 1.000	111.8 14.5 -1.29 1.000	116.5 12.2 -1.87 0.998	119.1 9.8 -2.49 0.988
-3	73.8 12.7 0.11 1.000	83.9 14.3 -0.14 1.000	93.2 14.8 -0.45 1.000	101.3 14.2 -0.77 1.000	107.7 13.0 -1.11 1.000	112.3 11.3 -1.51 0.998	115.1 9.5 -1.88 0.988

U.S.

ΔT̄ (°C)	ΔP̄(%) -30	-20	-10	0	10	20	30
3	59.2 12.5 0.24 0.995	68.7 13.8 0.06 0.995	77.4 14.1 -0.14 0.995	84.5 13.3 -0.34 0.995	89.4 11.9 -0.46 0.995	92.5 10.6 -0.54 0.995	94.5 9.3 -0.67 0.994
2	64.5 12.6 0.09 1.000	74.5 13.8 -0.12 1.000	83.5 14.0 -0.32 1.000	90.8 13.1 -0.58 1.000	95.8 11.5 -0.81 1.000	98.7 9.8 -0.99 1.000	100.3 8.4 -1.14 0.999
1	69.2 12.1 -0.05 1.000	79.6 13.1 -0.29 1.000	88.9 13.1 -0.51 1.000	96.3 12.0 -0.83 1.000	101.2 10.2 -1.23 1.000	103.9 8.3 -1.57 1.000	105.0 6.7 -1.74 1.000
0	72.6 11.1 -0.17 1.000	83.3 11.9 -0.43 1.000	92.6 11.7 -0.68 1.000	100.0 10.5 -1.09 1.000	104.8 8.4 -1.67 1.000	107.2 6.4 -2.25 1.000	107.9 5.0 -2.38 1.000
-1	74.2 9.8 -0.22 1.000	84.7 10.4 -0.46 1.000	94.0 10.1 -0.74 1.000	101.1 8.9 -1.14 1.000	105.8 7.1 -1.71 1.000	108.0 5.3 -2.25 1.000	108.5 4.4 -2.15 1.000
-2	74.1 8.3 -0.15 1.000	83.8 9.1 -0.31 1.000	92.6 9.0 -0.52 1.000	99.3 8.1 -0.75 1.000	103.6 7.0 -1.00 1.000	105.9 6.0 -1.26 1.000	106.5 5.6 -1.38 0.999
-3	72.3 7.1 0.02 0.995	80.9 8.1 -0.02 0.995	88.8 8.4 -0.17 0.995	94.8 8.1 -0.30 0.995	98.8 7.7 -0.37 0.995	101.1 7.4 -0.51 0.995	102.1 7.3 -0.66 0.994

Table E-2.2

RICE: *Expected-Yield Summary Tables*

INDIA

ΔT̄ (°C)	ΔP̄(%) -30	-20	-10	0	10	20	30
3	66.6	75.7	84.3	91.6	97.1	101.2	104.0
	9.5	10.6	11.1	10.2	8.9	7.6	6.2
	-0.03	-0.07	-0.36	-0.79	-1.11	-1.37	-1.72
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
2	69.5	78.5	87.2	94.9	100.6	104.7	107.1
	9.2	10.4	11.2	10.6	9.0	7.3	5.7
	-0.09	0.02	-0.22	-0.75	-1.26	-1.72	-2.18
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
1	72.2	81.1	89.9	97.7	103.5	107.5	109.6
	9.1	10.3	11.3	10.7	9.2	7.3	5.6
	-0.13	0.03	-0.19	-0.72	-1.29	-1.86	-2.30
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
0	74.4	83.4	92.2	100.0	105.9	109.7	111.6
	9.1	10.3	11.1	10.6	9.0	7.0	5.3
	-0.10	0.00	-0.24	-0.74	-1.34	-2.03	-2.49
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
-1	75.6	84.6	93.4	100.9	106.6	110.3	111.9
	9.0	10.1	10.8	10.2	8.6	6.6	5.0
	-0.09	-0.04	-0.32	-0.79	-1.40	-2.14	-2.63
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
-2	75.8	84.7	93.4	100.8	106.3	109.9	111.4
	8.6	10.1	10.7	10.0	8.4	6.4	4.8
	-0.02	0.03	-0.33	-0.84	-1.43	-2.13	-2.59
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
-3	76.0	84.6	92.7	99.2	104.0	107.2	108.8
	8.5	9.6	9.8	8.8	7.4	6.0	4.9
	-0.05	-0.08	-0.46	-0.96	-1.37	-1.66	-1.66
	1.000	1.000	1.000	1.000	1.000	1.000	0.998

PRC

ΔT̄ (°C)	ΔP̄(%) -30	-20	-10	0	10	20	30
3	75.1	81.8	87.9	92.7	96.0	97.8	98.4
	10.3	11.5	11.8	11.1	9.7	8.2	6.9
	-0.17	-0.19	-0.49	-0.91	-1.37	-1.81	-2.03
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
2	77.0	83.5	89.9	95.5	99.4	101.4	102.0
	9.6	11.2	12.2	11.8	10.4	8.7	7.4
	-0.02	0.14	-0.17	-0.66	-1.21	-1.68	-1.84
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
1	79.9	86.4	92.6	97.8	101.6	103.6	104.2
	10.3	11.6	12.3	11.8	10.4	8.8	7.6
	-0.12	-0.01	-0.30	-0.77	-1.31	-1.79	-1.95
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
0	82.1	88.8	95.0	100.0	103.4	105.2	105.6
	10.4	11.3	11.5	10.8	9.4	8.1	7.2
	-0.35	-0.30	-0.58	-1.04	-1.56	-1.94	-1.90
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
-1	81.8	88.9	95.0	99.6	102.6	104.1	104.4
	10.4	11.0	10.7	9.7	8.2	7.0	6.4
	-0.36	-0.46	-0.81	-1.31	-1.87	-2.16	-1.90
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
-2	79.9	87.1	93.2	97.8	100.7	102.1	102.3
	10.3	10.7	10.3	9.2	7.8	6.7	6.2
	-0.31	-0.54	-0.92	-1.41	-1.92	-2.15	-1.84
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
-3	76.2	83.0	88.7	92.9	95.7	97.2	97.7
	9.1	9.7	9.4	8.4	7.5	6.8	6.5
	-0.27	-0.48	-0.84	-1.22	-1.48	-1.47	-1.25
	1.000	1.000	1.000	1.000	1.000	0.995	0.978

Table E-2.3

SOYBEANS: *Expected-Yield Summary Tables*

BRAZIL

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%) -30	-20	-10	0	10	20	30
	53.0	61.8	70.4	77.6	83.3	87.5	90.4
3	8.5	10.0	10.7	10.4	9.5	8.4	7.2
	0.17	0.12	-0.11	-0.33	-0.47	-0.60	-0.77
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
	58.7	68.4	78.2	86.8	93.2	97.0	98.8
2	9.0	11.1	12.3	11.9	10.4	8.3	6.5
	0.29	0.24	-0.09	-0.49	-0.88	-1.21	-1.32
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
	65.0	75.4	85.8	94.7	100.9	104.2	105.1
1	9.8	11.7	12.7	11.9	9.8	7.3	5.6
	0.25	0.11	-0.24	-0.74	-1.33	-1.80	-1.65
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
	70.3	81.2	91.5	100.0	105.7	108.4	108.9
0	10.4	11.9	12.3	11.1	8.8	6.3	4.7
	0.14	-0.07	-0.42	-0.95	-1.67	-2.39	-2.29
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
	72.7	83.8	93.9	101.7	106.7	108.9	109.1
-1	10.9	12.1	12.0	10.4	8.0	5.7	4.2
	0.08	-0.21	-0.59	-1.14	-1.91	-2.69	-2.44
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
	73.0	83.8	93.3	100.5	105.0	106.9	106.9
-2	10.9	12.0	11.7	10.1	7.8	5.7	4.4
	0.10	-0.20	-0.61	-1.15	-1.77	-2.22	-1.84
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
	71.5	81.2	89.8	96.1	99.8	101.6	102.0
-3	10.2	11.4	11.4	9.9	8.0	6.4	5.2
	0.16	-0.04	-0.46	-0.93	-1.27	-1.37	-1.19
	1.000	1.000	1.000	1.000	1.000	1.000	0.998

U.S.

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%) -30	-20	-10	0	10	20	30
	61.5	70.6	79.9	87.9	94.1	98.9	102.1
3	10.6	12.3	13.5	13.4	12.6	11.7	10.5
	0.19	0.20	0.01	-0.22	-0.36	-0.51	-0.75
	0.995	0.995	0.995	0.995	0.995	0.995	0.994
	66.0	75.1	84.6	93.2	99.7	104.4	107.4
2	10.8	12.5	13.6	13.4	12.3	10.9	9.3
	0.17	0.15	-0.10	-0.42	-0.67	-0.90	-1.19
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
	70.3	79.4	88.9	97.5	104.2	108.8	111.4
1	10.5	12.1	13.0	12.6	11.1	9.4	7.7
	-0.01	-0.06	-0.33	-0.68	-1.04	-1.37	-1.66
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	73.4	82.6	91.8	100.0	106.5	110.9	113.2
0	9.3	10.7	11.3	10.8	9.4	7.7	6.2
	-0.20	-0.28	-0.54	-0.90	-1.34	-1.77	-1.98
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	74.4	83.5	92.2	99.9	106.0	110.2	112.3
-1	7.9	9.0	9.5	9.1	8.0	6.7	5.7
	-0.18	-0.27	-0.51	-0.81	-1.15	-1.48	-1.52
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	73.5	82.1	90.3	97.3	102.8	106.7	108.9
-2	7.0	8.0	8.4	8.2	7.7	7.1	6.7
	-0.03	-0.10	-0.31	-0.49	-0.64	-0.85	-1.02
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
	71.0	78.9	86.5	92.8	97.6	101.2	103.3
-3	6.5	7.6	8.1	8.1	8.1	8.1	8.1
	0.09	0.05	-0.12	-0.26	-0.30	-0.41	-0.55
	0.995	0.995	0.995	0.995	0.995	0.995	0.994

Table E-2.4

SPRING WHEAT: *Expected-Yield Summary Tables*

CANADA

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%)						
	-30	-20	-10	0	10	20	30
3	64.4	75.1	86.4	96.9	106.0	113.8	120.5
	10.4	13.0	15.1	15.8	15.3	14.4	13.1
	0.17	0.29	0.13	-0.16	-0.46	-0.75	-1.08
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
2	66.6	77.5	89.5	100.9	110.2	117.2	122.6
	10.3	13.1	15.4	15.8	14.5	12.5	10.6
	0.29	0.37	0.06	-0.40	-0.87	-1.31	-1.69
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
1	68.7	79.5	91.1	102.2	111.1	117.7	122.3
	10.2	12.6	14.5	14.4	12.8	10.6	8.6
	0.19	0.18	-0.15	-0.64	-1.17	-1.68	-2.08
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
0	69.1	79.8	90.5	100.0	107.6	113.3	117.4
	9.4	11.2	12.3	12.0	11.0	9.9	9.0
	0.07	-0.00	-0.27	-0.62	-0.88	-1.03	-1.12
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
-1	65.9	75.8	85.3	93.4	99.6	104.1	107.4
	8.4	9.9	10.8	10.8	10.5	10.4	10.6
	0.19	0.10	-0.11	-0.34	-0.40	-0.37	-0.38
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
-2	59.9	68.0	75.8	82.6	87.9	91.8	94.6
	7.4	9.0	10.4	11.2	11.3	11.3	11.5
	0.30	0.30	0.18	-0.01	-0.16	-0.20	-0.17
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
-3	52.7	58.7	64.6	69.9	74.4	78.0	80.7
	7.0	8.3	9.5	10.6	11.3	11.6	11.8
	0.08	0.21	0.27	0.26	0.18	0.09	0.04
	1.000	1.000	1.000	1.000	1.000	1.000	0.999

U.S.

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%)						
	-30	-20	-10	0	10	20	30
3	63.8	72.0	80.5	88.1	94.3	99.4	103.6
	9.3	11.1	12.4	12.5	12.0	11.2	10.2
	0.07	0.25	0.08	-0.17	-0.36	-0.53	-0.76
	0.999	0.999	0.999	0.999	0.999	0.999	0.998
2	67.5	75.8	85.0	93.3	99.9	104.8	108.6
	9.2	11.3	12.9	13.0	12.0	10.8	9.5
	0.19	0.34	0.05	-0.34	-0.64	-0.87	-1.10
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
1	71.2	79.6	88.8	97.5	104.3	109.3	112.8
	9.2	11.2	12.7	12.6	11.3	9.7	8.2
	0.11	0.20	-0.12	-0.57	-0.99	-1.32	-1.59
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
0	74.1	82.6	91.6	100.0	106.7	111.6	115.0
	8.5	10.3	11.6	11.4	10.1	8.3	6.7
	-0.06	0.06	-0.24	-0.72	-1.23	-1.71	-2.15
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
-1	75.7	83.9	92.6	100.6	106.9	111.5	114.6
	7.7	9.2	10.3	10.1	8.8	7.2	5.6
	-0.12	0.04	-0.25	-0.73	-1.25	-1.77	-2.21
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
-2	76.0	83.8	91.8	99.1	104.9	109.2	112.1
	7.1	8.3	9.2	9.0	8.1	6.8	5.6
	-0.14	0.05	-0.19	-0.59	-0.97	-1.31	-1.55
	1.000	1.000	1.000	1.000	1.000	1.000	0.999
-3	74.4	81.8	89.0	95.4	100.6	104.7	107.6
	6.9	7.7	8.4	8.4	7.9	7.3	6.6
	-0.13	0.01	-0.11	-0.34	-0.51	-0.65	-0.77
	0.999	0.999	0.999	0.999	0.999	0.999	0.998

Table E-2.5

SPRING WHEAT: *Expected-Yield Summary Tables*

USSR

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%)						
	-30	-20	-10	0	10	20	30
3	58.3	71.6	85.1	96.6	105.9	113.5	119.9
	13.1	16.3	17.9	17.3	15.9	14.6	13.4
	0.33	0.23	-0.16	-0.56	-0.80	-0.92	-1.05
	0.999	0.999	0.999	0.999	0.999	0.999	0.997
2	60.1	73.3	87.4	99.6	109.1	116.6	122.6
	12.8	16.4	18.4	17.5	15.5	13.6	12.2
	0.43	0.32	-0.15	-0.69	-1.07	-1.25	-1.34
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
1	62.1	75.1	88.8	101.0	110.5	117.8	123.6
	12.8	16.1	17.8	16.9	14.7	12.6	11.0
	0.34	0.19	-0.25	-0.83	-1.31	-1.54	-1.58
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
0	62.9	75.6	88.6	100.0	109.0	115.9	121.4
	11.9	14.6	15.9	15.1	13.2	11.4	10.1
	0.21	0.04	-0.35	-0.87	-1.30	-1.46	-1.37
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
-1	61.5	73.3	85.3	95.8	104.1	110.4	115.4
	10.4	12.7	13.9	13.4	11.9	10.5	9.7
	0.18	0.06	-0.28	-0.69	-1.00	-1.02	-0.80
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
-2	58.9	69.3	79.8	89.1	96.6	102.3	106.8
	9.1	11.1	12.2	12.1	11.3	10.5	9.9
	0.16	0.11	-0.12	-0.41	-0.60	-0.63	-0.53
	1.000	1.000	1.000	1.000	1.000	1.000	0.998
-3	55.0	64.2	73.1	80.9	87.2	92.3	96.4
	8.3	9.8	10.8	11.1	11.0	10.8	10.7
	0.16	0.13	0.01	-0.12	-0.19	-0.24	-0.27
	0.999	0.999	0.999	0.999	0.999	0.999	0.997

Table E-2.6

WINTER WHEAT: *Expected-Yield Summary Tables*

ARGENTINA

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%) -30	-20	-10	0	10	20	30
3	55.3	64.4	72.9	80.3	86.2	90.9	94.2
	12.3	14.1	14.8	14.5	13.5	12.1	10.5
	0.26	0.08	-0.19	-0.49	-0.80	-1.14	-1.54
	1.000	1.000	1.000	1.000	1.000	0.998	0.988
2	60.7	70.9	80.5	88.5	94.6	98.7	101.2
	13.6	15.6	16.4	15.6	13.9	11.7	9.6
	0.26	0.05	-0.29	-0.71	-1.17	-1.69	-2.26
	1.000	1.000	1.000	1.000	1.000	0.998	0.988
1	65.8	76.7	86.7	95.0	100.9	104.6	106.7
	14.5	16.3	16.7	15.6	13.4	10.9	8.6
	0.18	-0.08	-0.44	-0.91	-1.47	-2.13	-2.86
	1.000	1.000	1.000	1.000	1.000	0.998	0.988
0	70.4	81.8	91.9	100.0	105.6	108.9	110.5
	15.2	16.7	16.6	15.2	12.8	10.2	7.9
	0.10	-0.21	-0.60	-1.09	-1.70	-2.45	-3.26
	1.000	1.000	1.000	1.000	1.000	0.998	0.988
-1	73.4	85.1	95.2	103.0	108.1	110.8	111.8
	15.7	16.7	16.2	14.4	11.8	9.2	7.1
	-0.01	-0.35	-0.75	-1.28	-1.97	-2.77	-3.46
	1.000	1.000	1.000	1.000	1.000	0.998	0.988
-2	74.2	85.6	95.4	102.8	107.7	110.2	111.0
	15.1	16.0	15.5	13.7	11.2	8.8	6.9
	-0.09	-0.39	-0.76	-1.28	-1.94	-2.64	-3.07
	1.000	1.000	1.000	1.000	1.000	0.998	0.988
-3	73.0	83.3	92.2	98.9	103.5	106.2	107.4
	13.5	14.5	14.0	12.4	10.2	8.2	6.5
	-0.10	-0.35	-0.76	-1.28	-1.86	-2.47	-2.89
	1.000	1.000	1.000	1.000	1.000	0.998	0.988

AUSTRALIA

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%) -30	-20	-10	0	10	20	30
3	50.0	59.2	68.4	77.4	86.1	94.2	101.0
	18.7	21.7	24.1	26.0	27.3	27.8	27.4
	0.65	0.48	0.31	0.13	-0.06	-0.27	-0.49
	0.998	0.998	0.998	0.998	0.996	0.989	0.965
2	56.2	66.6	76.5	85.9	94.5	102.2	108.6
	20.3	23.4	25.5	26.8	27.5	27.6	27.0
	0.50	0.30	0.09	-0.10	-0.28	-0.46	-0.65
	1.000	1.000	1.000	1.000	0.999	0.991	0.967
1	61.8	73.2	84.1	93.9	102.6	110.1	116.2
	21.0	24.2	26.0	26.7	26.8	26.4	25.6
	0.37	0.14	-0.11	-0.33	-0.52	-0.70	-0.87
	1.000	1.000	1.000	1.000	0.999	0.991	0.967
0	66.2	78.3	89.8	100.0	108.8	116.2	122.2
	20.8	24.0	25.6	25.9	25.5	24.7	23.6
	0.25	0.02	-0.26	-0.53	-0.77	-0.97	-1.15
	1.000	1.000	1.000	1.000	0.999	0.991	0.967
-1	69.1	81.5	93.2	103.7	112.6	119.9	125.7
	20.1	23.0	24.5	24.7	24.0	22.9	21.6
	0.16	-0.08	-0.36	-0.65	-0.93	-1.18	-1.40
	1.000	1.000	1.000	1.000	0.999	0.991	0.967
-2	70.5	82.7	94.2	104.7	113.7	121.2	127.1
	19.0	21.6	22.9	23.2	22.6	21.5	20.2
	0.08	-0.16	-0.44	-0.71	-0.98	-1.24	-1.49
	1.000	1.000	1.000	1.000	0.999	0.991	0.967
-3	70.7	82.3	93.4	103.5	112.5	120.1	126.4
	17.7	20.0	21.2	21.5	21.3	20.5	19.5
	0.01	-0.22	-0.48	-0.72	-0.93	-1.15	-1.38
	0.998	0.998	0.998	0.998	0.997	0.989	0.966

Table E-2.7

WINTER WHEAT: *Expected-Yield Summary Tables*

INDIA

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%)						
	-30	-20	-10	0	10	20	30
3	59.4	64.9	70.3	75.0	78.9	81.9	84.3
	9.3	10.7	11.8	12.1	11.8	11.3	10.6
	0.17	0.33	0.28	0.13	-0.05	-0.19	-0.30
	1.000	1.000	1.000	1.000	1.000	0.999	0.991
2	66.2	72.4	78.8	84.6	89.1	92.3	94.5
	9.7	11.5	12.9	13.2	12.6	11.6	10.6
	0.25	0.37	0.17	-0.16	-0.45	-0.64	-0.70
	1.000	1.000	1.000	1.000	1.000	0.999	0.991
1	73.1	79.8	86.7	93.0	97.9	101.4	103.8
	10.2	12.0	13.2	13.2	12.3	11.0	9.9
	0.21	0.25	-0.02	-0.40	-0.75	-0.97	-1.03
	1.000	1.000	1.000	1.000	1.000	0.999	0.991
0	79.5	86.6	93.7	100.0	105.0	108.6	111.2
	10.1	11.8	12.8	12.5	11.4	10.1	8.9
	0.06	0.09	-0.21	-0.62	-1.01	-1.32	-1.51
	1.000	1.000	1.000	1.000	1.000	0.999	0.991
-1	84.5	91.7	98.8	105.1	109.9	113.5	116.0
	9.7	11.3	12.1	11.7	10.5	9.0	7.7
	0.06	0.10	-0.26	-0.71	-1.17	-1.57	-1.91
	1.000	1.000	1.000	1.000	1.000	0.999	0.991
-2	89.5	96.4	103.2	109.2	113.8	117.2	119.6
	9.9	11.2	11.8	11.2	9.9	8.4	7.1
	0.09	0.06	-0.32	-0.80	-1.28	-1.72	-2.11
	1.000	1.000	1.000	1.000	1.000	0.999	0.991
-3	94.5	101.5	107.9	113.1	117.1	120.1	122.2
	10.0	10.9	10.9	10.0	8.7	7.4	6.1
	-0.09	-0.20	-0.57	-1.07	-1.57	-2.05	-2.51
	1.000	1.000	1.000	1.000	1.000	0.999	0.991

PRC

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%)						
	-30	-20	-10	0	10	20	30
3	66.7	77.1	87.4	96.8	105.3	112.8	119.0
	14.5	17.0	18.5	19.1	19.2	18.7	17.8
	0.16	0.04	-0.19	-0.41	-0.61	-0.83	-1.08
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
2	67.9	78.0	88.3	97.9	106.4	113.5	119.4
	14.0	17.0	19.0	19.5	19.1	18.2	17.0
	0.34	0.26	-0.08	-0.42	-0.72	-0.98	-1.24
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
1	70.6	80.6	90.6	99.8	107.8	114.5	119.9
	14.4	17.0	18.6	18.9	18.3	17.3	16.0
	0.25	0.12	-0.21	-0.56	-0.89	-1.17	-1.44
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
0	72.3	82.1	91.5	100.0	107.4	113.6	118.6
	13.8	15.7	16.8	16.8	16.1	15.2	14.1
	0.04	-0.11	-0.40	-0.73	-1.03	-1.30	-1.55
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
-1	71.9	80.9	89.3	96.7	103.1	108.6	113.1
	12.6	13.9	14.3	14.1	13.5	12.8	12.0
	-0.10	-0.31	-0.59	-0.86	-1.08	-1.27	-1.45
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
-2	69.7	77.7	85.0	91.6	97.3	102.2	106.2
	10.9	11.9	12.2	12.0	11.6	11.1	10.4
	-0.26	-0.40	-0.62	-0.85	-1.03	-1.19	-1.33
	1.000	1.000	1.000	1.000	1.000	0.995	0.978
-3	66.4	72.9	79.1	84.8	90.1	94.7	98.6
	8.8	9.5	10.0	10.3	10.4	10.2	9.7
	-0.47	-0.44	-0.48	-0.57	-0.70	-0.87	-1.06
	1.000	1.000	1.000	1.000	1.030	0.995	0.978

Table E-2.8

WINTER WHEAT: *Expected-Yield Summary Tables*

U.S.

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%) -30	-20	-10	0	10	20	30
3	66.0	73.2	81.0	88.2	94.4	99.7	103.9
	7.6	8.9	10.4	11.0	11.1	10.9	10.2
	-0.28	0.18	0.17	0.01	-0.09	-0.21	-0.39
	0.994	0.994	0.994	0.994	0.994	0.994	0.993
2	69.0	76.4	84.9	93.1	99.9	105.3	109.5
	7.1	8.8	10.7	11.3	11.1	10.6	9.7
	-0.09	0.39	0.17	-0.11	-0.29	-0.45	-0.65
	0.999	0.999	0.999	0.999	0.999	0.999	0.999
1	71.7	79.4	88.4	97.2	104.5	110.1	114.2
	7.0	8.9	10.7	11.1	10.6	9.7	8.5
	0.05	0.39	0.05	-0.30	-0.56	-0.77	-1.03
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0	74.0	82.0	91.1	100.0	107.4	113.0	117.0
	6.8	8.7	10.3	10.4	9.6	8.3	6.9
	-0.02	0.27	-0.08	-0.47	-0.79	-1.10	-1.45
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
-1	75.5	83.5	92.5	101.0	108.2	113.5	117.2
	6.4	8.0	9.4	9.5	8.6	7.3	5.9
	-0.12	0.21	-0.10	-0.49	-0.82	-1.13	-1.45
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
-2	76.2	83.9	92.2	100.1	106.6	111.6	115.1
	6.0	7.3	8.5	8.7	8.1	7.2	6.3
	-0.18	0.21	-0.03	-0.33	-0.56	-0.78	-1.01
	0.999	0.999	0.999	0.999	0.999	0.999	0.999
-3	75.8	83.1	90.5	97.4	103.1	107.6	111.0
	5.7	6.7	7.7	8.0	7.9	7.6	7.1
	-0.17	0.19	0.08	-0.10	-0.20	-0.34	-0.52
	0.994	0.994	0.994	0.994	0.994	0.994	0.993

USSR

$\Delta\bar{T}$ (°C)	$\Delta\bar{P}$(%) -30	-20	-10	0	10	20	30
3	69.2	79.8	90.2	99.2	106.3	111.7	116.0
	8.3	9.7	10.5	9.9	8.6	7.3	6.2
	0.05	0.05	-0.25	-0.70	-1.00	-1.15	-1.29
	0.988	0.988	0.988	0.988	0.988	0.988	0.988
2	70.8	81.1	91.6	100.9	108.2	113.5	117.4
	8.2	9.8	10.9	10.4	8.9	7.4	6.1
	0.05	0.12	-0.21	-0.71	-1.15	-1.49	-1.69
	0.999	0.999	0.999	0.999	0.999	0.999	0.998
1	71.5	81.6	92.2	101.5	108.7	113.7	117.3
	8.3	10.2	11.6	11.2	9.7	8.2	7.1
	0.01	0.13	-0.22	-0.76	-1.28	-1.69	-1.89
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0	71.1	80.9	91.1	100.0	106.7	111.4	114.6
	8.9	11.1	12.7	12.6	11.5	10.3	9.5
	-0.04	0.09	-0.24	-0.72	-1.15	-1.44	-1.51
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
-1	69.0	78.1	87.5	95.6	101.7	106.0	109.0
	9.8	12.1	14.0	14.4	13.8	13.0	12.4
	0.01	0.13	-0.11	-0.46	-0.75	-0.90	-0.90
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
-2	65.4	73.5	81.6	88.7	94.2	98.2	101.2
	10.3	12.6	14.6	15.4	15.3	14.7	14.1
	0.14	0.29	0.15	-0.07	-0.25	-0.34	-0.35
	0.999	0.999	0.999	0.999	0.999	0.999	0.998
-3	60.9	68.0	74.9	81.0	85.9	89.7	92.8
	10.3	12.2	13.9	14.8	14.9	14.4	13.8
	0.30	0.48	0.45	0.33	0.22	0.13	0.09
	0.988	0.988	0.988	0.988	0.988	0.988	0.988

APPENDIX E–3

DISCOUNTING SOME OF THE UNCERTAINTY ABOUT THE CLIMATE SCENARIOS

INTRODUCTION

In Section 6–6 we showed the envelopes of the five climate scenarios for the northern lower middle (N-LM) latitudes (Figure VI-17). The overlap of these envelopes, which is typical of other latitude zones of agricultural interest, is not to be taken too literally, especially the overlap of possible temperature changes. For example, it defies reason that the envelope of the Same as the Last 30 Years Scenario, which has the second smallest spread of *global* temperature changes among the five climate scenarios, could encompass the expected *zonal* climate changes of *all* the scenarios. In this appendix we argue that some of the overlap is due to the way we interrogated the climate panelists in Task I and the way we processed their replies.[1]

THE UNCERTAINTY ABOUT TEMPERATURE CHANGES

Climatologists would certainly differ about the values of $\Delta\overline{T}$ that could materialize in a given zone of latitude under a particular climate scenario. Some residual uncertainty is unavoidable. In the first place, the ranges of *global* temperature changes in the climate scenarios allow for different configurations of *zonal* temperature changes. Furthermore, a wide zone of latitudes would not warm or cool uniformly. At the very least, one would expect a north-south temperature gradient across the zone.

Still, if the climate scenarios were constructed on the basis of non-overlapping intervals of global temperature changes, how does one account for the kind of temperature overlap seen in Figure VI-17? Part of the answer lies in our methodology. Each climate panelist was "assigned" to a climate scenario according to the mean of his projected *global* temperature changes. His temperature projections for the N-LM latitudes were then weighted and averaged with the projections of the other panelists assigned to the same scenario. Thus, the cohort of "moderate global warmers," for instance, consists of climatologists who individually perceived different ranges of *global* warming. Consequently, they perceived different ranges of *zonal* warming in the N-LM latitudes, and these ranges are fully reflected in Figure VI-17. The tendency of the methodology to overstate the range of zonal temperature changes is most evident in the Same as the Last 30 Years Scenario. This scenario had the largest number of "adherents" and the largest spread of temperature in the N-LM latitudes. The method of weighted averages captured the most extreme of their perceptions about zonal temperature change.

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[1] An obvious contributor is the shift of temperature cells, which extends the range of uncertainty about temperature by 0.5° C.

We believe that we could have got a sharper differentiation of zonal temperature changes among the scenarios if we had gone back to the panelists and posed conditional questions such as the following: Assuming a *global* warming of 0.25° C to 0.6° C (the limits of the Moderate Warming Scenario), what is the probability of an x-degree increase in the average temperature of the N-LM latitudes? A 2x-degree increase? Etc. We do not believe that a second survey of this sort would result in *expected* temperature changes much different from those based on the first survey. Hence, while we might have reduced the uncertainty about zonal temperature, the climate-crop scenarios would not have been greatly affected by the improved estimates of temperature change, a variable to which most yields are relatively insensitive.

THE UNCERTAINTY ABOUT PRECIPITATION CHANGES

The uncertainty about zonal precipitation and the sameness of the precipitation envelopes in Figure VI-17 are another matter because $\Delta\overline{P}$ is more important, in some senses, than $\Delta\overline{T}$. Besides, it is questionable whether one could elicit more definitive estimates of precipitation changes. The climate survey did ask conditional questions about zonal precipitation under assumptions of different, but small, temperature changes. The responses indicate uncertainty about even the direction of precipitation changes. In fact, the aggregated probabilities of increases greater than 10% and of decreases greater than 10% were usually not only small, but in some cases nearly equal. Consequently, the magnitudes of the *expected* changes were small, never exceeding 2% except for one latitude zone in one scenario, and the influence of precipitation on our climate-crop scenarios was very limited.

More useful precipitation estimates might result if one first got sharper projections of *zonal* temperatures for each scenario and then asked the panelists for conditional probabilities of precipitation changes based on the improved zonal temperature estimates. In addition, it would be desirable to make the revised precipitation questions more detailed. The original questions evoked only two independent probabilities based on a 10% threshold of change. One would prefer to have information similar to the frequency distributions of zonal temperature changes. And perhaps precipitation should be approached on the basis of crop regions rather than zones of latitude. An iteration of the climate survey along these lines would be futile, of course, if climatologists really are as uncertain and divided about temperature-precipitation relationships as the responses to the original survey seem to indicate. On the other hand, the small expected precipitation changes which evolved from the conflicting projections may contain a grain of "truth." There is some evidence suggesting that the effect of small climate changes on precipitation is indeed much less significant than the effect on temperature.[2]

Given the sensitivity of yields to precipitation, one would like to be more confident at least about the directions of precipitation change in the scenarios.

ASSUMPTIONS WHICH AFFECT THE CLIMATIC UNCERTAINTY

The limitations of a single climate questionnaire and the aggregation techniques of Task I inflated the climatic uncertainty. Two of our assumptions compounded the uncertainty problem.

For lack of anything better, we assumed *uniform* distributions of $\Delta\overline{P}$. Surely, some panelists would have perceived central tendencies in these distributions. Had we sought such perceptions, it is quite possible that we could have derived aggregated distributions of $\Delta\overline{P}$ with a central tendency that was forfeited by the assumption of uniformity. The similarly baseless assumption that $\Delta\overline{T}$ and $\Delta\overline{P}$ are *independent*, conjoined with the uniformity assumption, also works to reduce central tendencies in the distributions of zonal climate changes. The net effect of the two assumptions is to flatten (but not necessarily broaden) the joint distributions of $\Delta\overline{T}$ and $\Delta\overline{P}$ for the various latitude zones, i.e., to overstate the probabilities of some climate changes and to understate the probabilities of others. The two assumptions have a like effect on projected yields; they tend to flatten the distributions of the expected yields that are ostensibly possible in a given climate scenario.

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[2] See Appendix A of *Relating Climate Change to Its Effects*, Research Paper GC 78-10154, National Foreign Assessment Center, US Central Intelligence Agency, August 1978.

CONCLUSIONS

In summary, there are three possible ways to lessen the range of climatic uncertainty: by making additional inquiries of climatologists, by refining the method for aggregating their responses, and by seeking more cogent assumptions about the joint distributions of $\Delta\overline{T}$ and $\Delta\overline{P}$. We believe that the overstated uncertainty about temperatures could have been reduced, but that refined estimates would have had little effect on the expected zonal temperature changes and less effect on the crop-yield projections of Chapter III. We have to concede, though, that the uncertainty about precipitation, which tends to wash out any strong effects on yields, may be less amenable to reduction than the uncertainty about temperatures. Nor can we be sure that the expected values of "better" precipitation projections would be the same as those which we have used. At any rate, if the reader disputes the precipitation or temperature projections in Table S-1, he can construct his own climate-crop scenarios from the materials we have provided.

APPENDIX E–4

POSSIBLE REFINEMENTS OF THE CLIMATE SCENARIOS AND THE CLIMATE-RESPONSE MODEL

INTRODUCTION

We have learned how difficult it is to make a quantitative climate impact assessment, even for a single activity such as agriculture. Our subject is complicated and beset by uncertainties, i.e., knowledge gaps about which expert perceptions differ, to say the least. Were we able to start the project anew with the benefit of hindsight and more resources, we would do some things differently toward the ends of expanding the scope of the study, reducing uncertainty, incorporating greater detail, and validating the climate scenarios as well as the climate-response model. For anyone contemplating a similar assessment, we pass along a few broad thoughts about refining the study, with emphasis on Tasks I and II.

Our eclectic approach to the climate-crop problem has been quite fruitful, but the involvement of so many outside experts was time-consuming and cumbersome. Hence, retracing our steps may have a smaller payoff than an entirely fresh approach.

KEYING ON TASK III

In general agreement with common sense, the survey of the Climate Panel suggested that global climate is not apt to change drastically in the short span of 25 years. Subsequently, we found the effects of likely climatic changes on most key crops to be quite limited compared with the potential effects of changes in technology. Therefore, we would aim to develop climate-crop scenarios not only for 2000 AD but also for 2050, by which time some climatologists think carbon dioxide will have induced significant climate changes. Using this expanded time frame, we would work backwards from Task III to plan the requirements for Task II and Task I.

The Department of Agriculture's grain-oilseeds-livestock (GOL) economic model used in Task III covers many more crops and geographic regions than we dealt with in Task II. Hence we would increase the number of key country-crop combinations to narrow the gap between the crop coverage of Task II and the global coverage of the GOL model.

The GOL model is well suited for the main use to which it has been put, namely, the calculation of static equilibrium states in the global agricultural economy based on projected *average* yields. The model is less suited for simulating the dynamic nature of world agriculture—the shifts in production, trade and price patterns occasioned for the most part by the vagaries of crop weather in the major exporting and importing nations. In principle, Task II can furnish the spectra of national yields needed for a more dynamic global analysis.[1] However, we are unaware of any model that can rapidly calculate the economic consequences of a large number of global joint annual-yield events to which probabilities can be assigned. The magnitude of this problem is suggested in Section 4-4.

THE TECHNOLOGY QUANDARY

The treatment of technology in a follow-on climate impact assessment requires much attention. In Task II of the current study, technology was treated as an obstacle to be bypassed—a determinant of yield that needed to be factored out so that one could isolate the effects of climatic change on crop yields. The absolute values of the statistics generated by the GOL model are hostage to many assumptions, including assumptions about the effects of technology. The differences or ratios of these statistics, which are taken as measures of the incremental economic effects of the five climate scenarios, are probably less sensitive to the assumptions than the statistics themselves. A decision to generate more credible absolute statistics in the GOL model would change the basic orientation of the study and entail a different approach to technology in Task II.

Among the many exogenous inputs to the GOL model, expected yields are the ones of concern for the design of Task II. It is desirable that these expected yields reflect the combined effects of changes in both technology and climate. These effects are not independent, at least not in principle. One should consider not only the influence of climate on the rate of technology change, but also the fact that technology can modify the response of yields to climate changes. How to do this is an open question calling for a separate study of great intrinsic interest.[2] The slow rates of changes in yields due to technology and the even slower rates due to climate might permit the combined effects of technology and climate on yields to be approximated by a simple multiplicative or additive formulation.

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[1] See the subsequent section that deals with annual crop weather.

[2] Chapter II contains some suggestions for such a study.

The technology question is complicated by factors which influence the adoption of technology to a greater degree than climate. One is tempted to make the simplifying assumption that commodity prices are the prime determinants of planting and technology decisions. But this doesn't create a link to climatic change because prices are driven less by slow, long-term shifts in climate variables than by year-to-year fluctuations in crop weather and consequent changes in prices and national agricultural policies. Therefore, we are at a loss to say what kinds of additional technology questions could usefully be asked in a second-generation Task II.

THE ANNUAL-YIELD FUNCTIONS

What is much clearer is that in Task II we would want to ask the same kind of question about the response of yields to annual crop weather that was posed in the original questionnaire (Appendix A-1). Basically, the question is how, for one or more assumed states of technology, the key crops respond to changes in a small set of crop-weather variables. Two variables, say an average temperature and an average precipitation, would be preferable so as to preserve the simplicity and transparency of the climate-response model. However, we would study the desirability of introducing additional variables for greater realism and assess the feasibility of doing so.[3] On practical grounds, extra variables would rule out the survey technique we used for yield functions of two variables. An annual-yield function of three or more variables would be feasible only if it could be constructed from first principles, empirical data and copious judgment.

If we were to develop yield functions as we did in the present study, we would try to have the same number of respondents and the same average expertise for each of the key crops.[4] We would want first to experiment with the current annual-yield data bases to establish optimal levels of participation and expertise. Our computer program enables us to construct an annual-yield function from the responses of any subset of panelists. This capability was exercised in a limited way on the data base for U.S. corn. We found that the aggregated yield function of three selected "Experts" differed significantly from the aggregated yield function of all 11 U.S. corn "Experts." The latter function, in turn, had essentially the same shape as that of the total U.S. corn data base (the 11 "expert" estimates plus 12 less-than-expert estimates). However, the annual-yield response surface of all 23 respondents was systematically shifted one-half degree Celsius from the surface of the 11 "Experts." Thus, too small a data base may fail to capture the uncertainty in the community of experts, while too large a data base may exaggerate that uncertainty to the detriment of the yield projections.

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[3] These additional variables could be different averages of temperature or precipitation; length of growing season might be an appropriate variable for crops in the higher latitudes. One might use different sets of yield variables for different crops.

[4] The disparities in participation and expertise among the present data bases of the key crops are examined in Section 4-9. Clearly, it would be necessary to engage additional panelists who specialize in non-U.S. crops.

Whatever the provenance of the annual-yield functions in an iteration of Task II, we would attempt to test them against the record of historical yields. And, as a matter of general interest, we would pursue a question which was broached in Section 5-6: How can one explain the country-to-country differences among yield surfaces of the same crop?

In connection with the yield functions, one should consider the direct effect of carbon dioxide (CO_2) on crop yields. S. H. Wittwer, of Michigan State University, believes that this phenomenon may be important in assessing the agricultural effects of climate scenarios which hinge on rising levels of CO_2. The climate panelists who inclined toward global warming tended to cite increased concentrations of atmospheric CO_2 as a cause of the projected warming. Now, as we have seen, warming *per se* may enhance or depress yields, depending on the annual-yield function of the particular country-crop combination. Carbon dioxide can therefore have an indirect effect on yields to the extent that it is responsible for global warming. This indirect effect may require a correction to account for the fact that many crop yields are directly enhanced by higher concentrations of ambient CO_2. Hence, higher levels of CO_2 could reinforce the beneficial effect of warming in some cases and mitigate the adverse effects of warming in other cases.

Irrigated crops were not handled satisfactorily in the current study. Obviously, if a large proportion of a crop is irrigated, its yields could be less sensitive to climate change than if it were not. We did find that Indian rice, a largely irrigated crop, was quite insensitive to the five climate scenarios. But we may have got something close to the "right" answers about Indian rice for the wrong reasons: its apparent insensitivity is attributable to the fact that the expected climate changes in the northern subtropical latitudes all happen to lie near the contour curve for an expected yield of 100 (see Figure VI-3). A more cogent treatment of irrigated crops would require resolution of some of the nettlesome technology dilemmas.

Finally, in the interest of realism, we would try to allow for discontinuities in the annual-yield functions of Task II. For example, one of our agriculture panelists contends that a certain amount of cooling would have little effect on the yields of Canadian spring wheat in some regions, but that the shortened growing season would completely exclude the crop from other regions where it is now grown successfully. In reality, Canadian spring wheat production could drop while average yields were remaining relatively constant. Therefore, the general problem of yield discontinuities carries over into Task III, where the primary concern is production rather than yields. Moreover, total world grain production could be more resilient to climatic change than the annual-yield functions and the Canadian wheat example might suggest. Given the availability of suitable soils, shifts in growing areas and crop substitutions could materially affect the conclusions drawn from Task III. Accounting for such shifts and substitutions would be no easy matter.

THE TREATMENT OF ANNUAL CROP WEATHER

The choice of crop-weather variables for an iteration of Task II would determine not only the multivariate distributions needed to serve as the analogs of the present bivariate normal distributions (BNDs), but also the kinds of questions that would have to be put to the climatologists. We would try to establish whether the historical distribution of the crop-weather variables in the Base Period could be satisfactorily approximated by a multivariate normal distribution (MND) or whether we should proceed with empirical distributions. We would disaggregate each crop region to compare the MNDs of its parts with the MND of the whole. If the parts differed significantly from the whole, we would need a way to aggregate the annual-yield distributions of the crop subregions.[5] Also, we would like to compare the MNDs for the cooler years of the Base Period with the MNDs for the warmer years, with a view toward having one set of MNDs for global cooling and another for global warming, provided the two sets were sufficiently different to contradict the present assumption that the same set of BNDs is applicable to all the climate scenarios.

Once the annual-yield functions and MNDs were in hand, we would extend the scope of the sensitivity analyses described in Section 5-10 to include the correlation coefficients as well as the standard deviations used in the MNDs. We would also make more sophisticated attempts to validate the Base-Period distributions of annual yields. These efforts might lead to a weighting of the crop-weather variables in the annual-yield functions or to refinements in the derivation of the MNDs.

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[5] The Canadian wheat example of the preceding section is an argument for subdividing a large crop region and developing MNDs for each of its parts.

In an iteration of Task II one would try to quantify the effects of droughts and monsoon failures, elements of the climate-crop scenarios to which we have paid only lip service. It would be necessary to normalize the projected frequencies of drought in a given climate scenario relative to the frequencies embodied in the Base-Period MNDs.

There remains a higher order question about weather, viz., the correlation of the annual crop-weather variables between growing regions of the key crops. In a preliminary investigation, P. R. Hayes examined the cross correlations among time series of heading-period temperatures and time series of weighted average annual precipitation.[6] For the 15 country-crop combinations of Task II he found only 14 cases where the magnitude of the correlation coefficient exceeded 0.25. Most of the cases could be explained on meteorological grounds (e.g., the often-noted inverse relationship between temperature and precipitation in a crop region) or geographical grounds (e.g., the positive relationship between both temperature and precipitation in the spring wheat regions of Canada and the U.S.). However, five cases—all of which could well be spurious—are perplexing because of the great distances between the crop regions. One of them involves a positive correlation of the temperatures affecting Soviet spring wheat and Indian rice, while the others are transpacific in nature (e.g., a negative correlation between the precipitation affecting wheat in Argentina and Australia). Hayes' findings indicate that, as a first approximation, one can assume independence for the annual crop weather of noncontiguous crops. Further investigation of the correlation question might provide a basis for projecting distributions of annual global grain production in the climate scenarios.

THE TREATMENT OF CLIMATE CHANGE

The preceding discussion merely suggests the scope of things that one should decide about Tasks II and III before redesigning Task I to support its sequel. In Appendix E-3 we mentioned several possible improvements for Task I in connection with the uncertainties about zonal temperature and precipitation. The main changes in Task I would be an expansion of the time frame to the year 2050, an augmentation of the Climate Panel, and a concentration on the critical crop-weather variables. In addition, we would try to elicit—but not artificially force—a greater consensus about changes in the critical variables.

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[6] P. R. Hayes, "The Correlation of Droughts Between the Major Grain Producing Regions of the World," Final Report to the National Defense University, September 1978. This study was supported by the Kettering Foundation.

First, we would solicit only projections of *global* temperature.[7] The intermediate projections of global temperatures to the year 2000 by the new members of the Climate Panel could be used to validate or modify the global temperature boundaries and the "probabilities" of the current climate scenarios. Again, the panelists would be asked to assign weights to the factors they perceived as likely causes of global temperature changes.

Once the global temperature boundaries of the scenarios were established, for each interval of global temperature we would seek conditional probabilities of the following:

- Changes in the long-term averages of the critical temperature and precipitation variables (or their proxies) by latitude zone or crop region,
- Changes in the correlation and standard deviations of the critical crop-weather variables by zone or region, and
- The frequencies of drought and monsoon failures in the growing areas of the key crops.

The panelists would be asked to flag any special effects, like continentality, that had caused them to hedge on their conditional probabilities. Perhaps a second round of zonal/regional questions would help to reduce the uncertainty found in the first round, especially if the questions were amended to remedy defects pointed out by the panelists.

At any rate, the residual climatic uncertainty should be quantified so that its effects on the crop-yield projections could be traced. It would be easier to evaluate the residual uncertainty and its implications if participation and expertise were nearly uniform in all details of the final climate scenarios. The various details of the present climate scenarios are a very mixed bag from the standpoint of expertise and numbers of respondents.[8] Uniformity could be achieved by having a larger Climate Panel with some members selected for specific specialties. Targeting specialties would provide a hedge against low participation, and a larger number of panelists would permit the use of subsets of respondents to achieve consistent levels of expertise.

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[7] In Task I we implicitly equated the Climate Panel's projections of temperature changes in the northern hemisphere with global temperature changes. One of the panelists, J. Gentilli, believes that recorded (hence future) temperature trends in the northern hemisphere may not be representative of global trends. However, for the climate-crop scenarios we used the panel's projections of *zonal* temperature changes, and these projections were not formally predicated on either global or hemispheric changes. Global temperature nevertheless seems to be a natural first criterion for the construction of climate scenarios.

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[8] See Appendix C in *Climate Change to the Year 2000.*

Absent "better" projections of precipitation, one might proliferate the climate-crop scenarios in order to highlight the importance of precipitation for crop yields. That is, one could retain the canonical climate-crop scenarios based, as in the present study, on the *expected values* of zonal precipitation changes, and append to each of them two scenarios based on greater and lesser precipitation changes. Even if no "probabilities" of occurrence could logically be ascribed to them, the additional "precipitation" scenarios would indicate how much the yield distributions could depart from the canonical projections if the expected values of precipitation were in error.

DISCLAIMER

Despite the title of this appendix, we are not sure that all the mentioned "possible refinements" are in fact possible. The tentative and imprecise suggestions need to be fleshed out, evaluated and costed in order to develop a workable program with reasonable prospects of success. We feel that the present uncertainty in the climate scenarios can be reduced, but we do not know by how much or at what price. As for the climate-response model, the main challenge is to strike a level of aggregation that balances realism and practicability.